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SUPERCONDUCTIVE 7.2-TESLA FOUR-MAGNET ASSEMBLY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

FOREWORD

The research described herein, which was conducted by RCA Electronic Components, was performed under NASA Contract NAS 3-7928. The Project Manager was Mr. Charles S. Corcoran, Jr., Space Power Systems Division, NASA-Lewis Research Center, with Mr. James C. Laurence, Electromagnetic Propulsion Division, NASA-Lewis Research Center, as Technical Advisor.

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INTRODUCTION

The Lewis Research Center is the NASA organization primarily responsible for the development of space power and propulsion systems. Many advanced space power and propulsion systems planned by the Lewis Research Center require magnetic fields that may be supplied best by superconductive magnet systems.

Because of these needs, the NASA Lewis Research Center accordingly supported two contracts with RCA to study the feasibility of large-volume, high-field-strength superconductive electromagnets.[1] The feasibility was demonstrated as a result of these studies, and RCA was awarded a further contract to design and develop a 15-cm-bore, 14-Tesla magnet.[2] While this magnet was being designed, a hardware contract was awarded to RCA for the design, fabrication, and testing of a system, consisting of four magnets and a Dewar, that would develop 7.2 Teslas in a 50.8-cm-diameter winding bore.[3] This summary report covers the latter system.

The design of these magnets was based upon the use of niobium stannide (Nb_3Sn) superconductive ribbon wound in layer form with associated techniques (e.g., use of special interleaving and shorting strips) that had proved successful in many previously constructed high-field magnets. Modular construction was used to contain mechanically the large forces that develop and to facilitate winding, powering, and testing of subgroups of coils. Specific superconductors were designed for use in local regions of the magnet to allow for differing requirements of current-carrying capacity at the field ranges and for varying hoop stresses.

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1. Contracts NAS 3-2520 and NAS 3-5420.
2. Contract NAS 3-7101.
3. Contract NAS 3-7928.

The combined use of these concepts culminated in the superconductive magnet shown in Figure 1. Additional parts of the system are a 96.5-cm-ID liquid-helium (liquid-He) Dewar, part of which is shown in Figure 2, and a power supply and control system that previously was supplied under Contract NAS 3-7101.

Figure 1. Assembly of Four Magnets with Compression Spacers Before Mounting on Support Tube.

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VAPOR-COOLED
POWER LEAD
VENT LINE

CENTER FIELD
MR PROBE

LIQUID-HELIUM
FILL LINE

LIQUID-NITROGEN
SUPPLY

HELIUM GAS
RECOVERY LINE

LIQUID-HELIUM-
LEVEL
PROBE

VAPOR-
COOLED
LEAD TERMINAL

NITROGEN VENT
FROM LID

VALVE AND
102-CM-ID
LINE TO
VACUUM PUMP

SPRING-LOADED
PRESSURE RELIEF
PORT

NITROGEN VENT
FROM JACKET
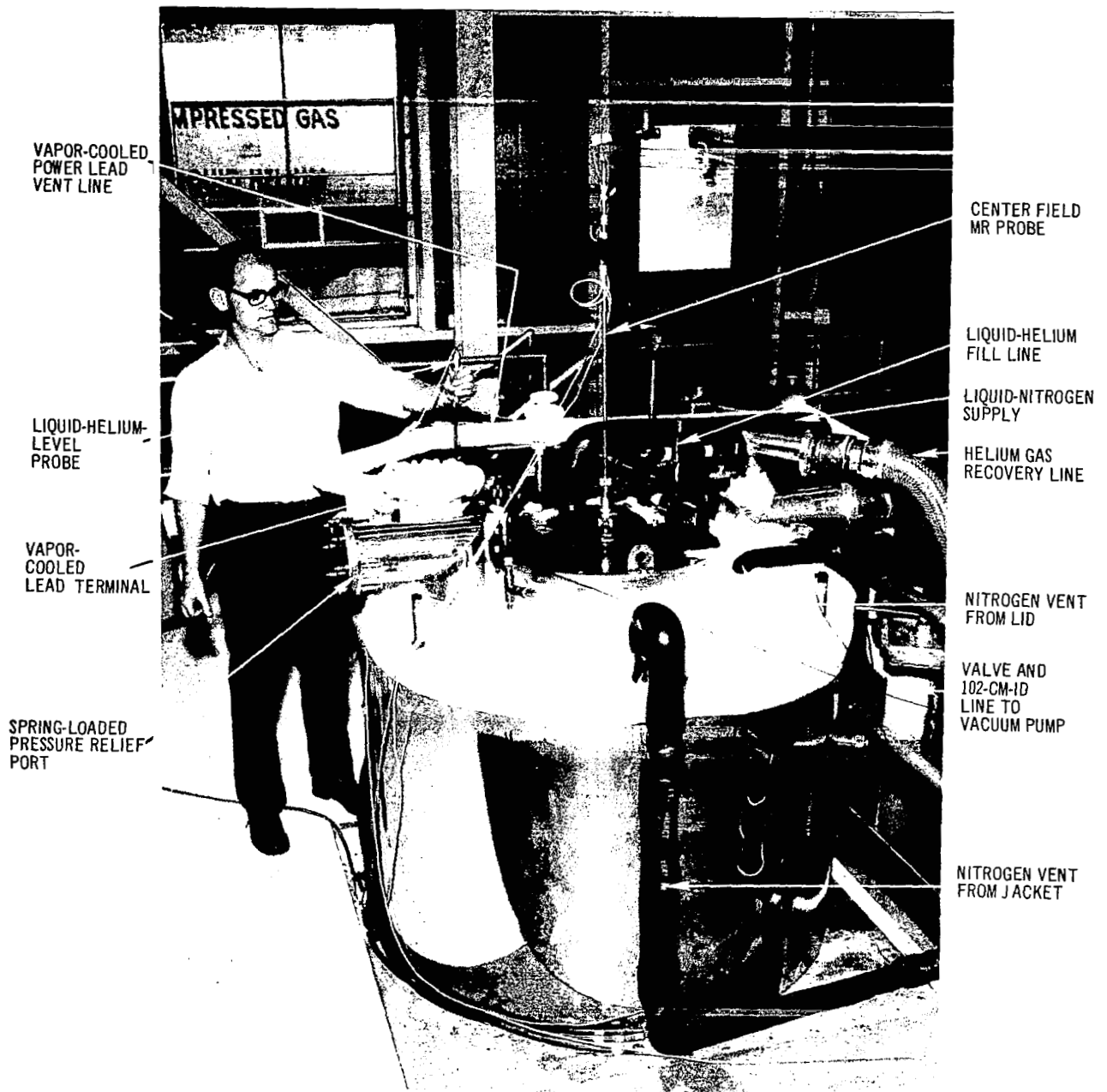
Figure 2. 96.5-CM-ID Liquid-Helium Dewar with Top Portion Connected
to Vapor-Cooled Power Leads and Helium-Recovery Apparatus

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SECTION II
SYSTEM CONSIDERATIONS

A. BACKGROUND

Essentially two requirements were placed upon the magnet designs:

   a. The four magnets, each with 10.2-cm-long axial windings and 50.8-cm-ID winding bore and with 15.2 cm between the windings of adjacent magnets when stacked, must develop 7.2 Teslas at the magnet system centroid.

   b. Each magnet separately must develop 4 Teslas at its own centroid.

An additional requirement was that magnet currents could be no greater than 100 amperes. The reason for this requirement was so that a power supply system being designed concurrently under NAS 3-7101 would be compatible with the 7.2-Tesla system.

A Dewar and mounting system was required so that a single magnet or any combination of the four magnets could be tested.

Because of axial forces that would be developed within this four-magnet system plus some forces anticipated due to future additions of end magnets, the magnet structure was required to be strong enough to transfer safely 2,670,000 newtons of force across the central plane of the four-magnet system.

B. SYSTEM DESIGN

1. GENERAL MAGNET-DESIGN CRITERIA

The magnet system design was determined by the requirements to achieve 4 Teslas in the individual magnet, 7.2 Teslas in the system, and a reasonable outer dimension for the magnets to avoid future complications when special "doughnut" Dewars would be constructed. Due to the restriction on all axial

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dimensions of the magnets, producing the required single magnet field of 4 Teslas is possible only by having enough current density for any chosen outer magnet dimension. Figure 3 shows the approximate manner in which the outer diameter of the magnet must change to maintain the 4-Tesla central field as average current density within the outer confines of the total single-magnet windings (i.e., internal magnet mechanical structure included) changes. At the design current density of 14.9 kiloamperes/cm^2 selected eventually, the slope of this function is an increase in outer diameter of approximately 2.8 cm for each decrease in current density of 1 kiloampere/cm^2. At 12 kilo-amperes/cm^2, the increase in outer diameter is 4.7 cm per decrease of 1 kilo-ampere/cm^2. At the outer diameters considered, each radial increase of 1 cm corresponds to approximately 10,000 additional meters of 0.23-cm-wide super-conductive ribbon. Increasingly severe penelties, therefore, are paid in size and cost as overall current density is made lower.

Because extremely high axial forces must be transmitted through the magnet structure when the four magnets are assembled in a system, a magnet must be composed of modules that have sufficient structural cross section in a plane perpendicular to the magnet axis. By iterative-type calculations[4], the confines of the extremes of the windings of a single magnet require for structure a volume of 18-½ percent. The design current density within the actual layers of windings then increases from 14.9 to 18.3 kiloamperes/cm^2.

An additional factor affects the need to design for the highest feasi-ble current density. The stored energy of the four-magnet system is 7.1 mega-joules, of which approximately 2 megajoules is required for each magnet of the central pair. Following the design philosophy established under contract NAS 3-7101, it was necessary to provide normal metal energy sinks into which currents could be induced upon normalcy to provide for controlled energy dissipation.

4. E. R. Schrader and P. A. Thompson, "Use of Superconductors with Varied Characteristics for Optimized Design of Large Bore High-Field Magnets," IEEE Trans. on Magnetics, Vol. 2, No. 3, p. 311, September 1966.

NOTE: DESIGN POINT CURRENT DENSITY IS
BASED UPON SHADED CROSS-SECTION AREA,
WHICH INCLUDES SOME COIL-FORM STRUCTURE
AND VOIDS.

25.4 CM
WINDING
RADIUS

4 TESLAS

J WITHIN ACTUAL WINDINGS

DESIGN POINT
FOR AVERAGE J
(SEE NOTE.)

OD OF WINDINGS (CM)

AVERAGE CURRENT DENSITY (J) (kA/CM^2)

02692L
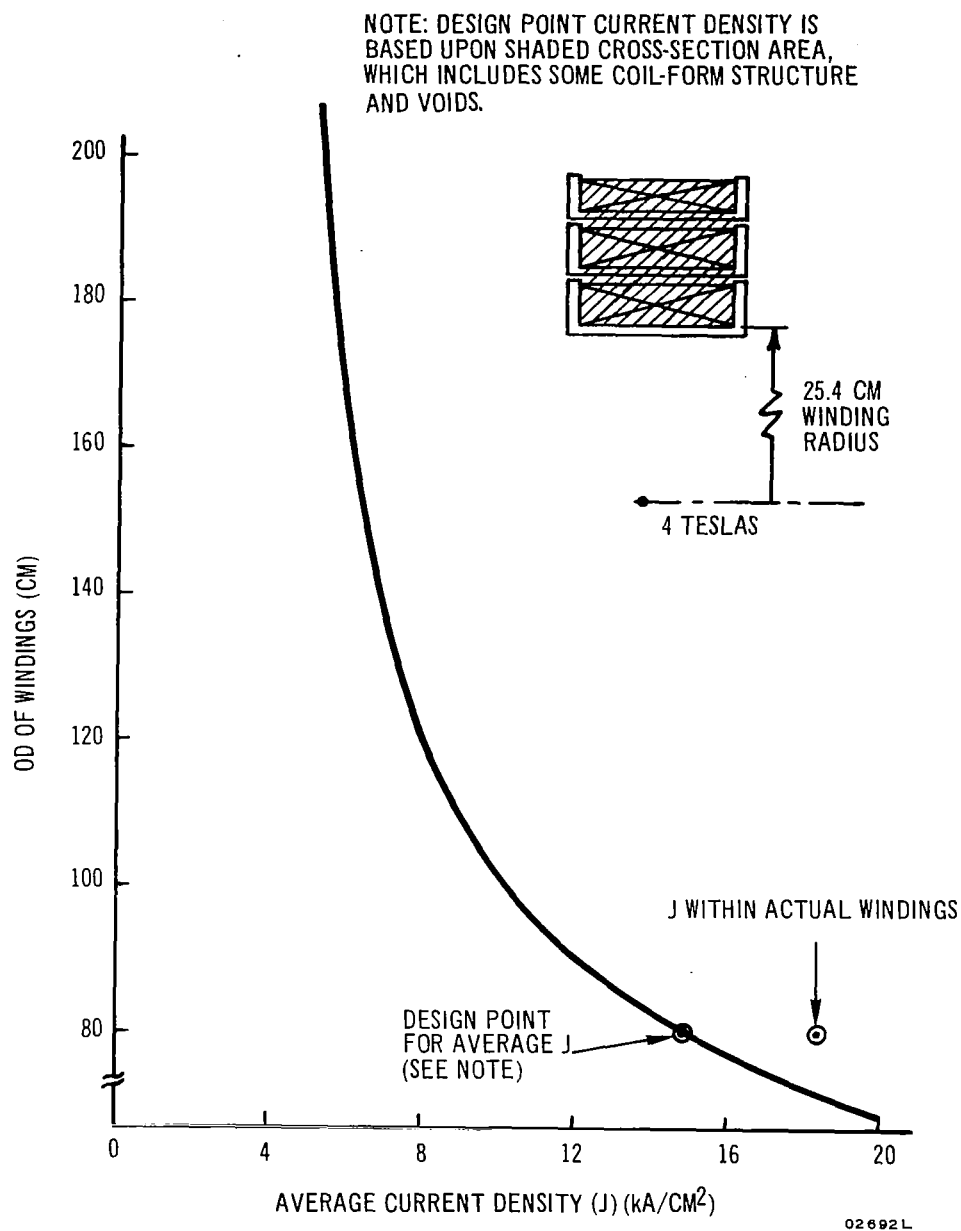
Figure 3. Single Magnet, Outer Diameter vs. Average Current Density to
Develop 4 Teslas in a 50-CM-ID Winding

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A portion of these shorted-turn-type energy sinks is provided by shorting the copper sheets used as part of the interleaving between wound layers of ribbon. The restriction on using the space between magnets, however, precluded further distribution of massive copper-shorted turns between winding volumes. The only remaining volume for a shorted secondary was outside the outer diameter of the magnet windings. The electrical characteristics of such a shorted turn could not be optimized analytically, due to the complex electromagnetic transients that accompany normalcy in a large superconductive magnet. The radial depth allowed for such an energy sink, therefore, is a matter of providing the maximum feasible volume of shorted copper while maintaining a reasonable outer diameter, so that the Dewar will not be too large. The volume devoted to the energy-sink ring is limited further by the need to contain the copper within a stainless-steel casing. If the copper is not contained, the copper can magneto-form and possibly burst upon occurrence of a magnet normalcy.

The thickness of the bobbin flanges was determined chiefly by the requirement for access ports every 90 degrees between magnets with a minimum segment dimension of 7.6 cm for each port. A compression spacer is not permitted at these points, and the bobbin flanges must sustain the combined axial pressure of the windings of each magnet. In the worst case, the steady-state windings pressure against the flange would be 2600 psi. Calculations made by File[5] indicate that 1.27-cm-thick flanges would limit the deflection of this cantilevered section to below 0.254 mm, the latter value being the maximum permissible dimension for the windings mass to shift locally.

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5. Calculations leading to the mechanical structure design were made under a consultation agreement with Dr. J. File of the Princeton Accelerator Research Laboratory, Princeton, New Jersey.

Nominal weights of magnet components are as follows:

    a.   Single magnet, 406 kilograms

    b.   Compression spacer, 39 kilograms

    c.   Four-magnet assembly, 2090 kilograms

2.   DEWAR

The Dewar requirements are those necessary for testing up to four magnets with the specified 15.2-cm spacing between windings with low helium boil-off losses.[6] Extra height was provided for the eventual testing of a larger magnet system to be made under contract NAS 3-9684. The Dewar inner diameter is 96 cm to accept the 90-cm maximum magnet diameter (including leads). The Dewar is shielded by liquid nitrogen that is contained in an outer jacket and in a removable upper lid. In addition to the liquid-nitrogen pot, the lid contains a set of eight nitrogen-cooled current leads. A set of 12 vapor-cooled current leads was added by NASA after delivery. Other ports are used for transfer lines and signal-lead access. Figure 2 shows the top portion of the Dewar.

Additional dimensional characteristics of the Dewar are as follows:

    a.   Depth (from a horizontal bar across top flange to center of Dewar bottom), 350 cm.

    b.   Outside diameter, 122 cm.

    c.   Maximum outside height (from base of Dewar to top of a pressure-release port), 430 cm.

    d.   Maximum working volume, 2000 liters.

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6.   Complete Dewar specifications are retained by the Electromagnetic Propulsion Division of the NASA Lewis Research Center, Cleveland, Ohio.

3. SINGLE 4-TESLA MAGNET

Using iterative techniques and the criteria mentioned in Paragraph B.1, the basic single-magnet design shown in cross section in Figure 4 was evolved. A photograph of an assembled single magnet is shown in Figure 5. Each magnet consists of three bobbins of 304 stainless steel. The bobbins serve both as winding forms and as structural members for the transmission of axial stresses in the full assembly of four magnets. The copper secondary turn, which serves as an energy sink, has approximately the same cross-sectional size as the bobbins and is situated outside the windings. The winding bobbins have milled radial slots on the inside of each flange for helium access to the superconductive ribbon layers.

One side of the outer bobbin flanges contains aligned milled slots for current and voltage leads, which are carried radially outward and over the outer circumference of the secondary copper turn and onto a Bakelite terminal board. All leads, therefore, are available at the outer diameter of the magnet, where they will not interfere with access space on the sides. This feature can be seen in Figure 5.

Tapped holes are located within the 1.17-cm-thick bobbin flanges to receive mounting bolts. A single magnet is assembled with stainless-steel straps, which are bolted to all modules to hold them together. When more than one magnet is assembled, compression spacers take the place of the straps between the magnets and are fastened to the same tapped holes in the flanges. Tests can be performed, therefore, on single modules or on modules in combination.

The design electromagnetic parameters of a single magnet are given in Figures 4 and 6. Preliminary test results of modules fabricated with copper shorting strips showed excessive time constants and a possibility of low critical currents. The shorting strips, therefore, were changed to phosphor bronze, and one of the four magnets was made with copper-clad ribbon, instead of silver-plated ribbon, for added stability. Ribbon designations for this magnet (later referred to as magnet II) are given in Figure 4. The fields

12.49

1.58

0.68

Cu SECONDARY TURN

MOD. C

10.16

MOD. B

44.13

11

MOD. A

1.17

0.68

24.76

30.73

35.81

39.52

37.7

SILVER   PLATED
RIBBON   VERSION
MAGNETS I, III, IV

COPPER   CLAD
RIBBON   VERSION
MAGNET II

INTER.
2.3 mil Cu
INTER.
0.0038CM Cu

RIBBON
R60216
MTRS, 16000

RIBBON, R60273
METERS, 15000
INTER., 0.0038CM Cu

RIBBON, R60283
METERS, 18000
INTERLEAVING, 0.0038CM Cu

RIBBON, R60301
METERS, 17000
INTER., 0.0038CM Cu

RIBBON, R60285
METERS, 16000
INTERLEAVING, 0.0038CM Cu

RIBBON, R60302
METERS, 15000
INTER., 0.0038CM Cu

NOTES:

1. ALL SHORTING STRIPS
   ARE 0.0025 X 1.27cm
   PHOSPHOR BRONZE

2. INTERLEAVING IS
   OFHC Cu HAVING A
   RESISTANCE RATIO OF
   > 150 WITH 0.0038CM
   MYLAR PER SIDE.

• DIMENSIONS IN CM.
• RIBBON LENGTHS APPROXIMATE

026931

Figure 4. Cross Section of Single Magnet with Ribbon and Interleaving Designations

Figure 5. Single Magnet Showing Assembly of Modules, Outer Shorted
Turn, Terminal Board, and Vertical Track

CU SECONDARY TURN

MOD C

| 4.30 | 4.41 |
| 0.48 | 4.96 |

MOD B

| 0.37 | 5.07 |
| 4.43 | 6.10 |

MOD A

| 3.25 | 5.75 |
| 8.44 | 7.26 |

NOTE:
ALL FIELD VALUES
IN TESLAS

4 T FOR I = 83 A
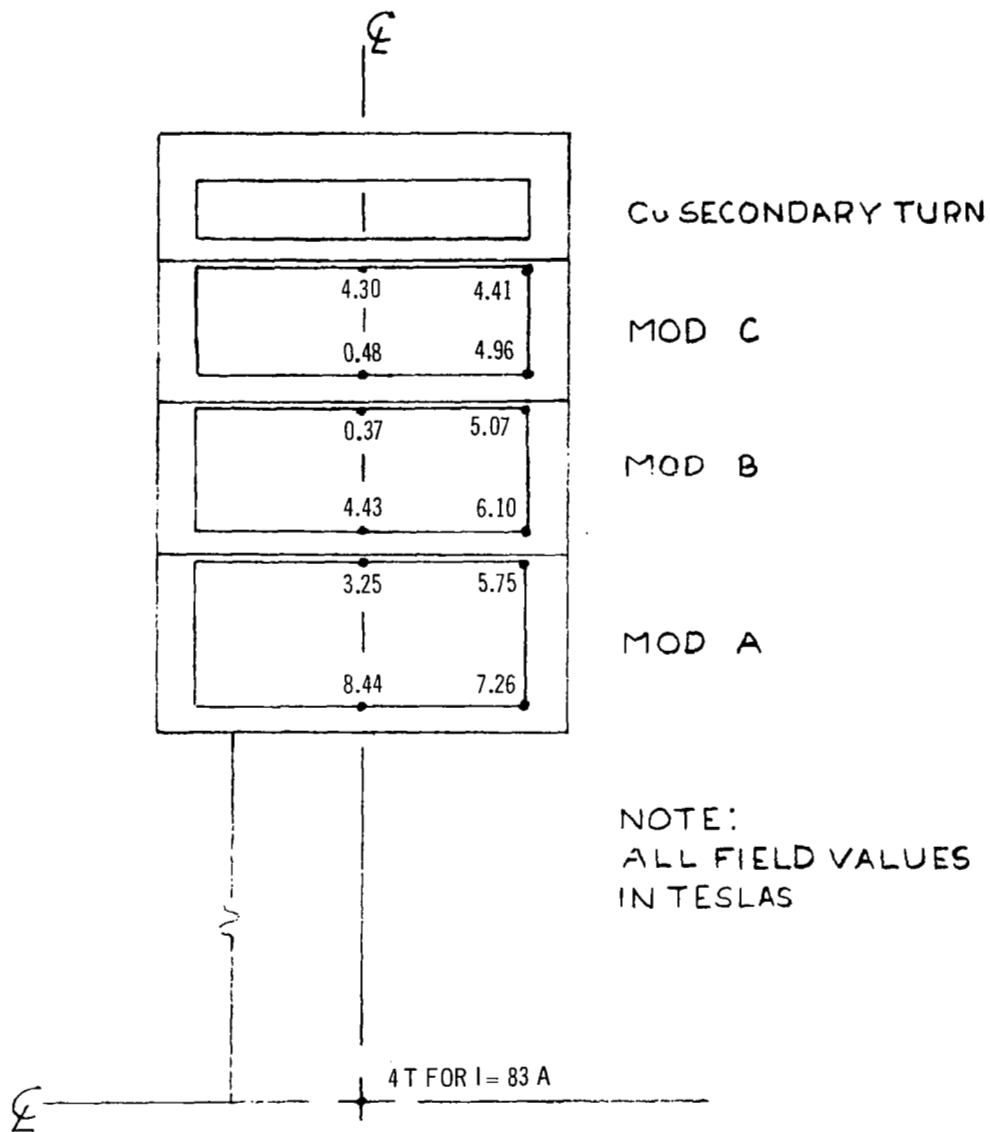
02695L

Figure 6. Single Magnet, Design Values of Magnetic Field Intensity at Important Points
in Module Windings (Averaged from Parameters of Those Wound
with Silver-Plated Ribbon)

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at the coil corners are approximately the same as those given in Figure 6 for the silver-plated-ribbon version. The only difference in the distribution of the designed current density is in outer module C, in which slightly heavier copper was used in the interleaving for the silver-plated version. To maintain a current density in the copper-clad version that is equal to that of the silver-plated version, the transport current of the copper-clad version had to be increased.

4. SYSTEM OF FOUR MAGNETS

The assembled system of four magnets (Figure 1) shows compression spacers between magnets. The compression spacers bolt to the magnet modules to form an integrated unit. Current and sensing contacts from the terminal boards on each magnet go to a single vertical current-lead channel (shown in Figure 1) and to sensing-lead channels (not shown). The complete magnet assembly is held onto the Dewar support tube in a manner similar to that shown in Figure 7.

The considerable axial forces expected at the field of 7.2 Teslas are shown in Figure 8. Figure 8 also indicates total magnetic field values at various winding locations, assuming a single current of 70.5 amperes in all windings.

Figure 9 shows the cross section of the four-magnet assembly in the lower half of the Dewar. The numbering and marking codes of the modules and magnets for orientation at the time of final testing are shown in Table I. Approximate field/current values at the system centroid are given to assist in calculating the total central field when different currents are used in each module.

Final fabrication parameters for each module are given in Table II. Physical characteristics of the ribbons are given in Table III. The minimum short-sample values of the ribbons are given in Figure 10. Part of magnet III (silver-plated-ribbon version wound first) was refabricated when it was noted after test 22 that the outer windings of each module had shifted. Folding of the outer protective tape that covers several further protective layers of
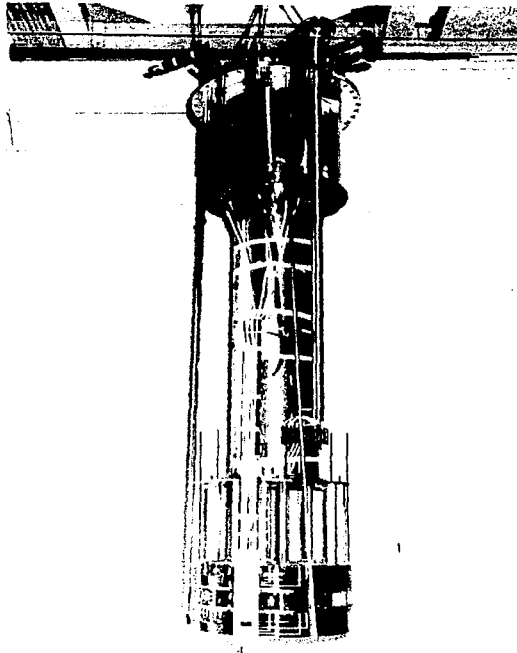
A. TWO MAGNETS MOUNTED ON EXTENSION RODS TO PLACE
MAGNETS AT LOWEST PORTION OF DEWAR
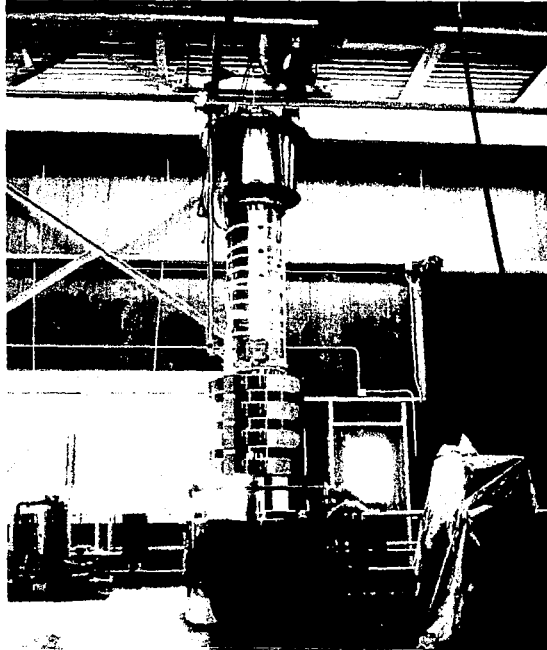
B. FOUR MAGNETS MOUNTED WITHOUT EXTENSION RODS

02696P

Figure 7. Mounting of Magnet Assembly to Dewar Support Tube
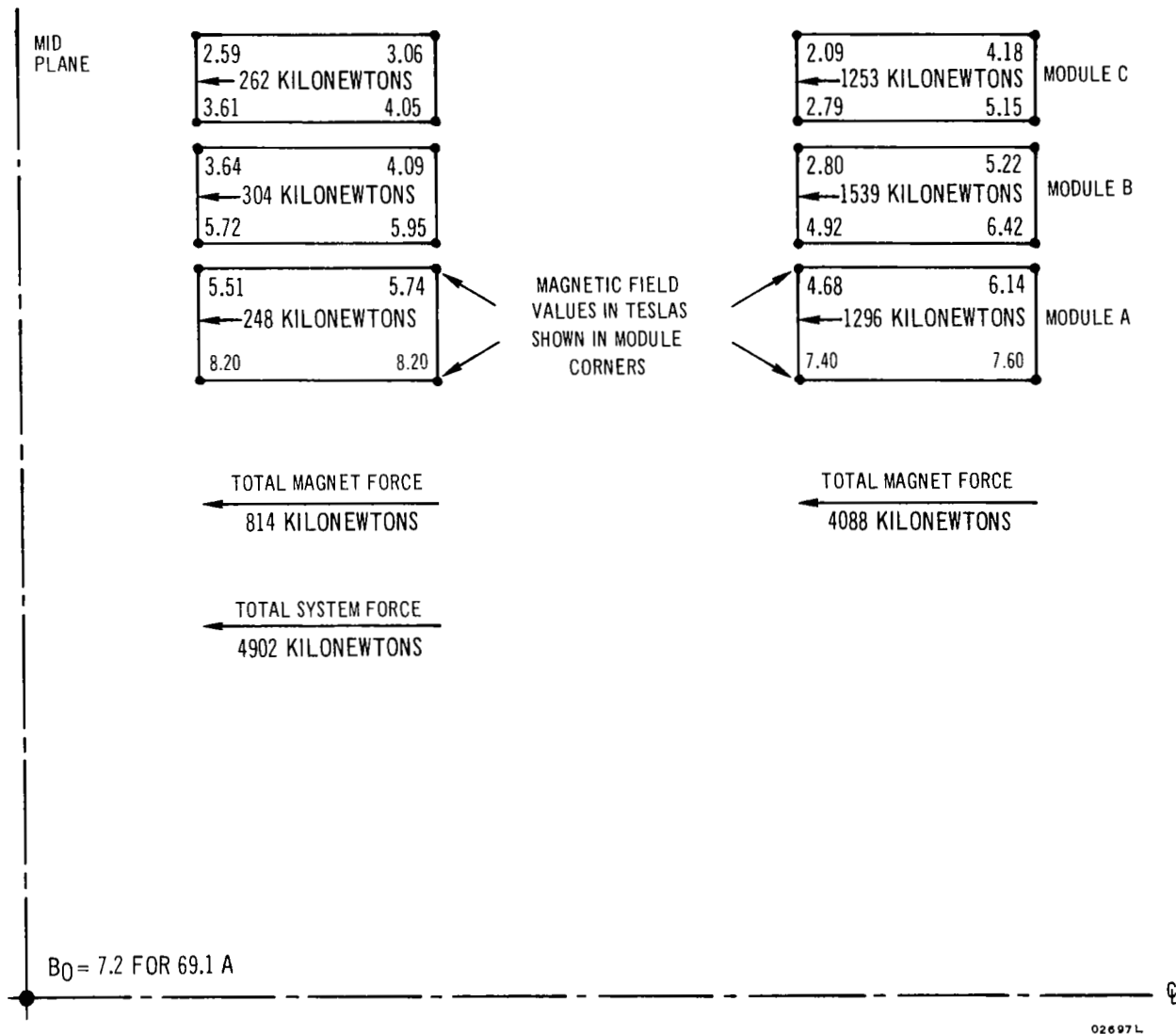
Figure 8. Axial Forces and Total Magnetic Fields for Magnet System
Consisting of Four Magnets of Type Shown in Figure 6
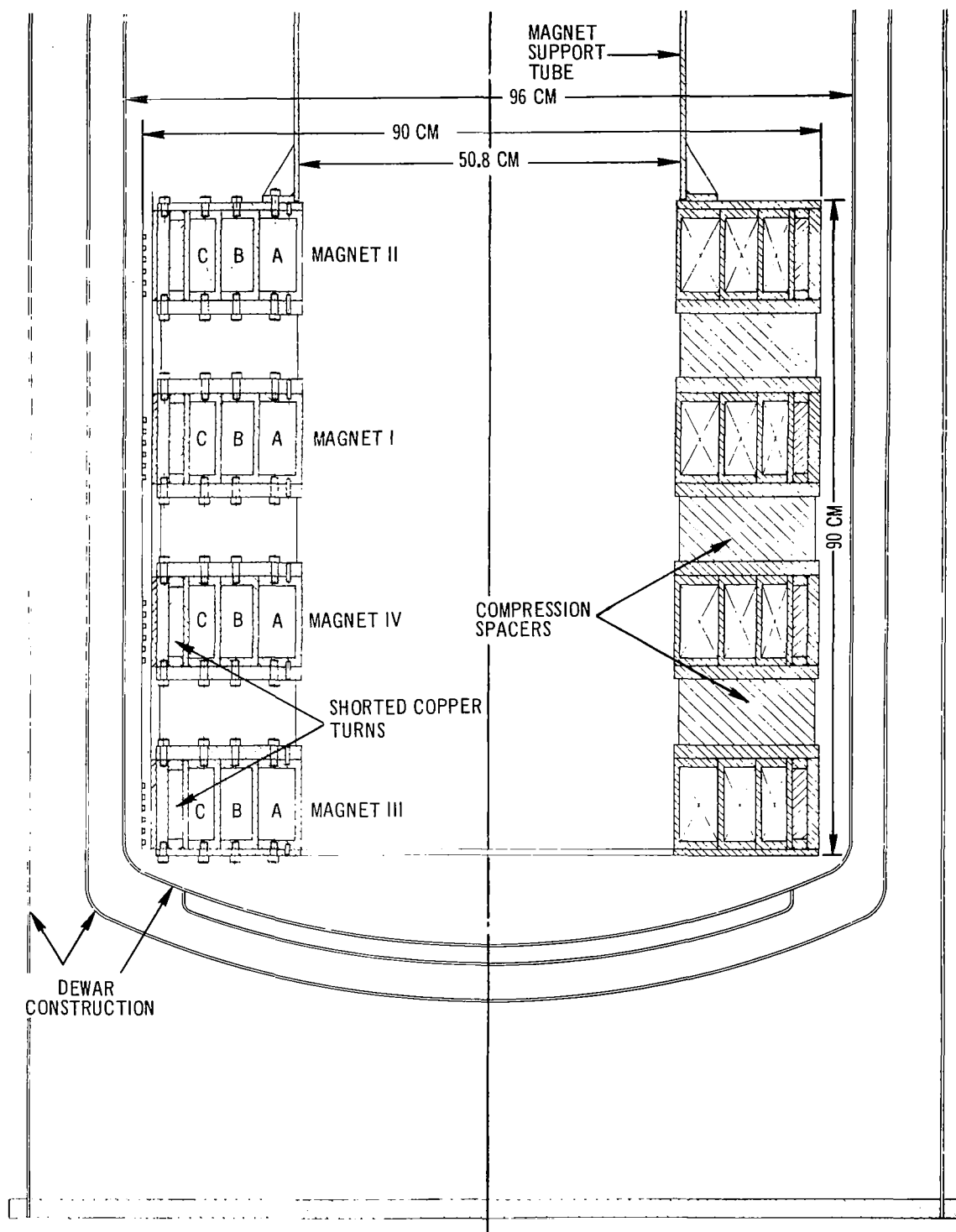
Figure 9. Cross Section of Four-Magnet Assembly in Lower Half of Dewar

TABLE I.   NUMBERING AND MARKING CODES OF MODULES AND MAGNETS

Magnet Number	Teslas $\times 10^{-4}$ per Ampere at Centroid					Module Identification Holes Located on Top Flange of Each Module		
	Single Module			Single Mag.	Four-Mag. System			
	Module A	Module B	Module C	Module A+B+C	Module A+B+C	Module A	Module B	Module C
I	200	160	110	470	385	• • • •	•	• •
II	185	152	103	440	95	• •	• •	• • •
III	200	160	110	470	103	• • •	• • •	• • • •
IV	200	160	110	470	385	•	• • • •	•
4 Mag. System	–	–	–	–	968			

TABLE II. MAGNET FABRICATION PARAMETERS

Magnet	Module	Ribbon Type	OD of Windings (cm)	Number of Turns	Number of Layers	Ribbon Length (Meters)
I	A-4	R60285	61.0	9368	231	16,473
I	B-1	R60283	70.7	8461	210	17,773
I	C-2	R60216	78.6	6679	166	15,901
II	A-2	R60273	61.1	8333	210	14,657
II	B-2	R60301	71.5	8142	194	17,190
II	C-3	R60302	78.5	6286	153	14,971
III	A-3	R60285	60.5	9061	218	15,867
III	B-3	R60283	70.9	8752	218	18,402
III	C-4	R60216	78.8	7001	168	16,678
IV	A-1	R60285	60.6	8911	222	15,622
IV	B-4	R60283	71.1	8616	213	17,455
IV	C-1	R60216	78.9	6899	172	16,438

TABLE III. NOMINAL DIMENSIONS OF Nb_3Sn RIBBONS

Silver-Plated Ribbon (Magnets I, III, IV)

Ribbon Type	Substrate Thickness (mm)	Nb_3Sn Thickness per Side (mm)	Silver Plate Thickness per Side (mm)	Total Conductor Thickness (mm)
R60285	0.102	0.0097	0.0254	0.172
R60283	0.076	0.0064	0.0254	0.140
R60261	0.046	0.0064	0.0254	0.110

Copper-Clad Ribbon (Magnet II)

Ribbon Type	Substrate Thickness (mm)	Nb_3Sn Thickness per Side (mm)	Copper Clad Thickness (mm)	Total Conductor Thickness (mm)
R60302	0.102	0.0097	0.0254	0.174
R60301	0.076	0.0064	0.0254	0.142
R60273	0.046	0.0064	0.0254	0.112

NOTE: Copper-clad ribbon is slightly thicker than equivalent silver-plated ribbon due to solder used during the cladding process.
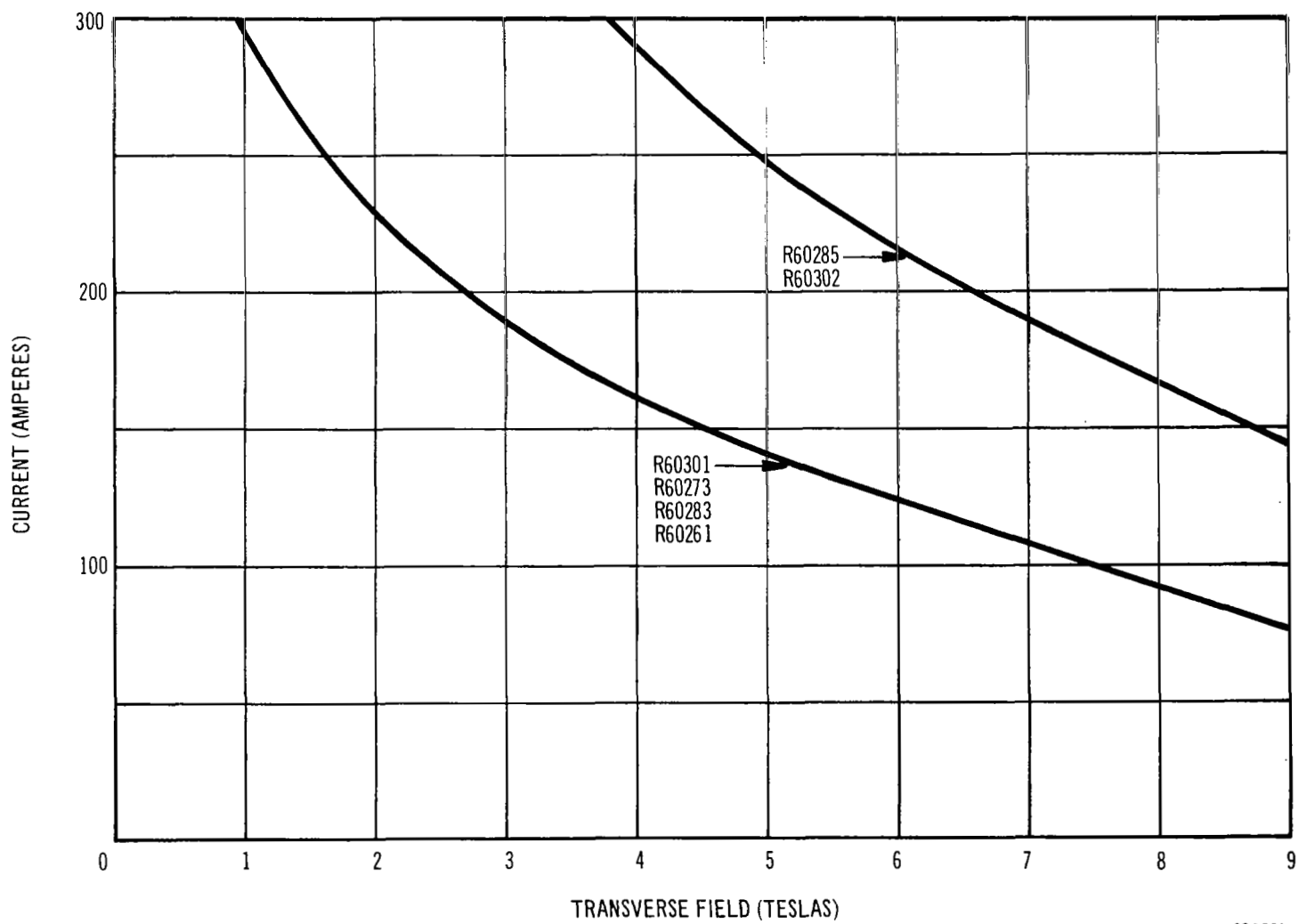
Figure 10. H-I Curves of Ribbon Types

Hastelloy ribbon is shown in A, Figure 11. The Hastelloy ribbon after the cloth tape was removed is shown in B, Figure 11. Similar problems were noted on the peripheries of modules A and B. It appeared, in each case, that the Hastelloy acted like a shorted turn; induced currents reacting with the magnet field caused local purturbations with accompanying buckling and shifting.

Upon unwrapping the Hastelloy and a layer of Teflon and interleaving, it was seen that physical movement of the Hastelloy dragged along parts of the outer few layers of Nb_3Sn and apparently resulted in some local damage and arcing. Each module was unwound, therefore, until no further damage was evident, and the module was rewound with new ribbon. The Hastelloy layers then were insulated from one another to minimize shorting.

A. BUCKLING EVIDENT AFTER TEST 22
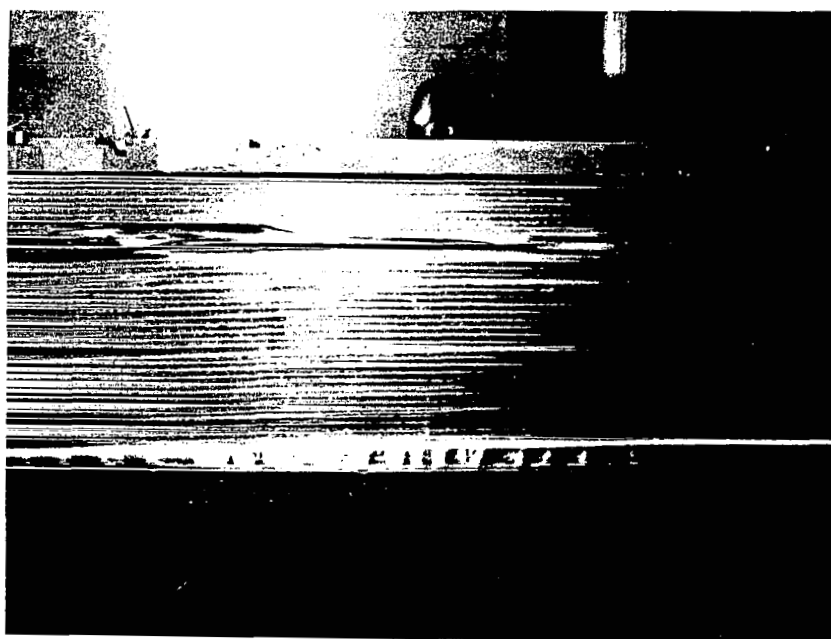
B. TAPE REMOVED TO EXPOSE HASTELLOY RIBBON

02700P

Figure 11. Module C of Magnet III Showing Shifted Outer Windings

SECTION III

ELECTRICAL SYSTEM

A. INDIVIDUAL MAGNETS

All current and voltage diagnostic leads from each of the three modules of an individual magnet exit along radial slots milled into the module flanges. Current leads are 1.27-cm-wide high-conductivity copper strips with two or three strands of superconductive ribbon soldered in parallel. Voltage leads are flat copper strips where they make pressure contact with the ribbon inside the windings; these leads are extended outside the windings as fine Teflon-coated wires. The outer periphery of the copper-stainless steel energy sink contains a Bakelite terminal board with anchor positions for all leads that are destined to be a permanent part of the individual magnet assembly. Each magnet, therefore, is a selfcontained unit requiring only external connections for operation.

B. MAGNET TERMINAL BOARD

As each module was wound, diagnostic voltage taps were installed at each current contact and usually across each ribbon splice. In most cases, initial tests of modules were conducted with these voltage taps soldered directly to a cable coming through the Dewar top, and the terminal boards were not used. This approach was used because the multitude of voltage taps are supplied to detect any obvious problems, such as resistive splices. After initial testing, most of these diagnostic·leads were pulled out of the windings, and the remaining leads were connected to the magnet terminal board. The latter leads serve as sources of signals for monitoring and for future diagnostics when needed.

Figure 12 shows the essential features of a magnet terminal board. Three 48-pin terminal boards, numbered I, II, and III at the lower right corner, are located to coincide with radial slots provided on the outside of the magnet

25
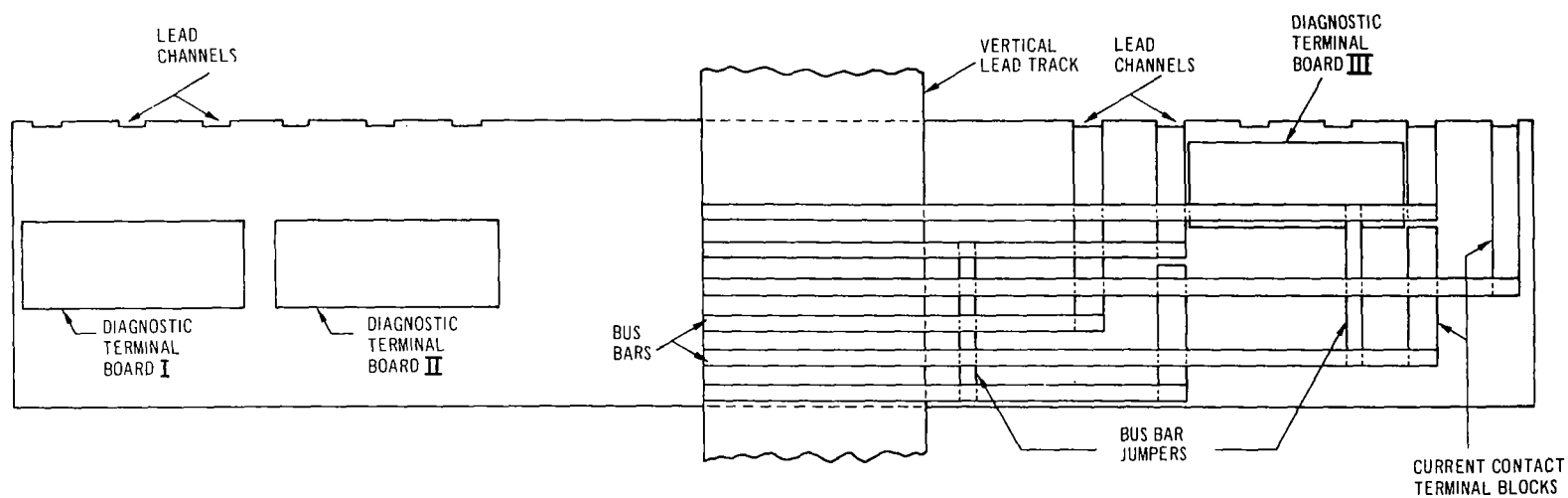
Figure 12. Magnet Terminal Boards and Bus Bars. Location Diagram

LEAD
CHANNELS

DIAGNOSTIC
TERMINAL
BOARD I

DIAGNOSTIC
TERMINAL
BOARD II

VERTICAL
LEAD TRACK

LEAD
CHANNELS

DIAGNOSTIC
TERMINAL
BOARD III

BUS
BARS

BUS BAR
JUMPERS

CURRENT CONTACT
TERMINAL BLOCKS

26

0270IL

flanges. Terminal identifications, which are identical for the three boards, are shown in Figure 13.

The current leads are arranged as indicated in Figure 9. The flexible copper leads (with paralleled superconductor leads) from the start and finish of each module winding are bent onto the terminal board and are soldered to a shaped copper terminal block. Square 0.64-cm copper bus bars, which are in milled slots in the Bakelite, are soldered to this terminal block. A screw supplements each soldered contact for safety. The bus bars, which are at right angles to the flexible strip leads and shaped terminal blocks, run along the terminal board to the approximate center, where they are bent out of their milled slots to a height above the terminal board that permits them to be placed in other milled slots in a vertical lead track. This vertical lead track is a 10.2-cm-wide Bakelite strip that supports the power leads (copper strips with parallel superconductors) and the 0.64-cm-square bus bars. Connection is made by soldering and by the use of binding screws at their junctions at each magnet location. Connections between magnets are made in the same manner as from magnet to outside power source, i.e., by junctions through the vertical lead track.

If two or three of the modules of any single magnet are to be connected in series, 0.64-cm-square copper jumpers are screwed and soldered to the bus bars as shown in Figure 12. Connections between modules of a magnet, therefore, are not made on the vertical lead track.

Tables IV through VII list actual terminal board connections for the voltage leads of magnets I through IV, respectively. The first voltage leads listed are connected at the inner (+) current contact. Subsequent voltage leads are located progressively outward in the windings of a module. The numbers assigned to voltage leads in the first column refer to a designation made at the initial winding. Gaps appear in the numbering sequence, because voltage leads were removed when they no longer were considered necessary. The location of any given lead, as it pertains to a given length of Nb_3Sn, is designated on the detailed magnet fabrication sheets at the NASA Lewis Research Center. For purposes of neatness and space saving, the original numbered
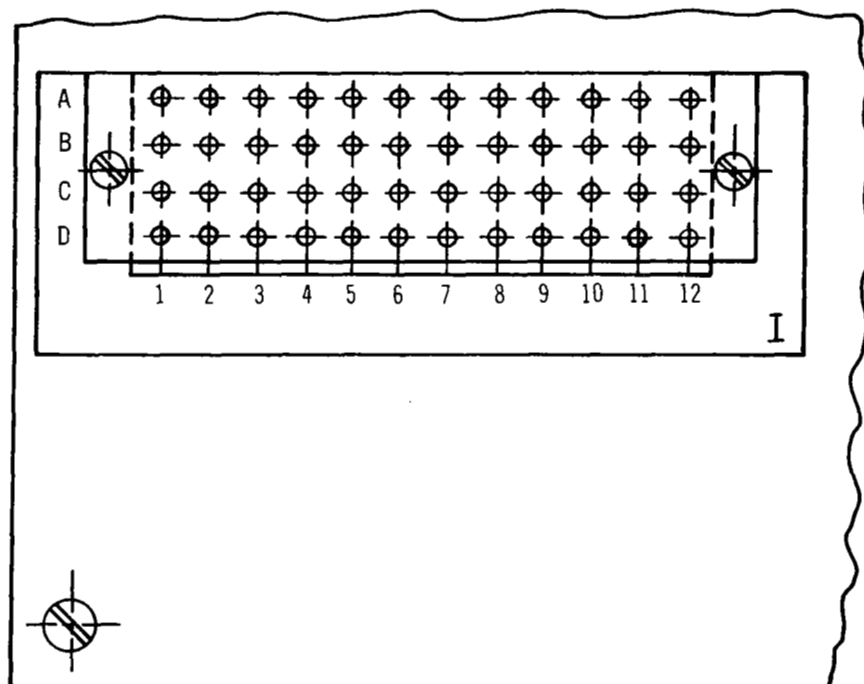
02702L

Figure 13. Terminal Boards I, II, and III, Terminal Identifications

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TABLE IV. TERMINAL BOARD CONNECTIONS FOR MAGNET I VOLTAGE LEADS

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
+E·coil	III	D10	+E·coil	III	C10	+E·coil	III	D1
+E·coil	III	D9	+E·coil	III	C11	+E·coil	III	D2
2	I	B1	1	III	D6	1	I	D12
8	I	B2	2	I	C6	3	I	C3
9	III	B4	3	II	C11	4	II	C8
11	II	B12	4	III	C6	5	I	D6
12	I	B3	5	I	C1	7	III	C8
14	III	C2	7	II	C5	8	I	C2
15	I	A11	9	I	B10	10	I	D7
20	I	B4	10	II	C6	11	I	D9
22	II	C1	13	I	D1	12	III	A11
23	I	A12	14	II	C10	13	II	D9
25	III	B2	15	I	B12	17	III	B7
26	I	A10	16	III	D7	18	I	C4
28	III	A6	17	III	A7	19	III	C9
29	II	C9	19	I	B11	20	I	D3
31	II	C2	22	I	A1	22	II	D8
32	II	C3	24	I	B6	23	III	A1
center contact	III	B8, B9	26	II	D11	24	I	C7
			29	III	C7	25	III	A10

TABLE IV.   TERMINAL BOARD CONNECTIONS FOR MAGNET I VOLTAGE LEADS (Cont.)

MODULE A · · · ·			MODULE B ·			MODULE C · ·		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
33	I	A9	30	I	D5	26	I	C11
36	I	B8	31	II	C7	center contact	II	B1
37	III	B12	32	III	B3			
38	II	C4	33	II	A12	center contact	II	D1
39	II	B5	34	III	A12			
40	I	A5	35	II	D2	28	I	D8
41	I	B5	36	I	C12	29	III	A8
43	I	C9	37	II	A1	30	I	C10
45	III	B11				31	I	D4
						32	III	A2
47	III	A5	40	I	A4	33	III	D11
48	II	D3	44	I	A3	34	II	D6
49	III	B10	46	I	B7	36	II	D10
50	II	D12	47	I	C5	38	I	C8
51	II	C12	48	I	A2	39	III	A9
53	III	A4	−E·coil	III	B1	40	II	D7
54	I	A6	−E·coil	III	C1	41	III	A3
56	I	A7	MR·coil	III	D3, D4	44	I	D10
57	II	D4				−E·coil	III	C3
58	I	B9				−E·coil	III	C4
59	II	B7				MR·coil	III	B5, B6

TABLE IV. TERMINAL BOARD CONNECTIONS FOR MAGNET I VOLTAGE LEADS (Cont.)

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
60	II	D5						
61	II	B8						
64	II	B9						
66	II	B6						
−E·coil	III	C12						
−E·coil	III	D12						
MR·coil	II	B10, B11						

TABLE V. TERMINAL BOARD CONNECTIONS FOR MAGNET II VOLTAGE LEADS

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
+E·coil	III	A12	+E·coil	III	B10	+E·coil	III	A5
3	I	A5	+E·coil	III	A10	2	III	C11
4	III	A4	6	I	D1	6	III	D6
6	II	A1	9	I	B11	7	III	D8
8	I	A10	10	I	B6	8	III	D10
10	II	A5	18	II	B5	12	II	C11
12	III	C1	20	I	B12	14	III	A9
14	III	B4	22	III	D7	center contact	II	C1
16	I	A1	center contact	III	B6			
18	III	A1				16	I	C2
center contact	III	C7	25	I	B10	18	I	C7
			28	II	B1	19	III	B8
20	III	A11	29	III	B12	22	III	B7
22	III	C5	32	II	B12	23	III	B11
24	III	D1	33	III	B3	24	I	C3
25	I	A4	34	III	A8	25	III	B9
30	III	D5	35	I	C12	26	III	D9
32	II	A6	31	I	B2	27	III	C9
34	III	A2	40	III	A3	28	III	A7
36	I	A2	41	II	B6	29	III	D12
38	I	A12	46	III	C12	30	II	C7

TABLE V. TERMINAL BOARD CONNECTIONS FOR MAGNET II VOLTAGE LEADS (Cont.)

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
39	II	A2	47	II	B11	33	I	D12
40	III	A6	49	III	C3	36	I	D3
44	I	A3	50	I	C11	37	III	C11
$-E \cdot coil$	III	D11	51	II	B7	40	I	D11
$MR \cdot coil$	II	A11, A12	53	I	B3	$-E \cdot coil$	III	D3
inductive coil	II	A9, A10	63	I	B1	$MR \cdot coil$	II	C5, C6
			$-E \cdot coil$	III	D4	inductive coil	II	D5, D6
			$MR \cdot coil$	III	C2, D2			

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TABLE VI.   TERMINAL BOARD CONNECTIONS FOR MAGNET III VOLTAGE LEADS

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
+E·coil	III	A7	+E coil	III	C10	+E·coil	III	Γ2
+E·coil	III	A8	+E coil	III	C11	+E·coil	III	D1
3	III	B5	2	I	B2	4	I	D8
22	III	B4	4	III	B9	center contact	II	C1
29	III	A9	5	III	A6			
39	III	A4	7	III	C12	22	III	D9
B	II	C11	11	III	B3	B	III	D11
C	I	A2	12	II	A1	C	III	D10
D	II	A2	13	II	D11	−E·coil	III	D3
−E·coil	III	B11	15	III	B12	−E·coil	III	D4
−E·coil	III	A11	18	III	C9			
MR·coil	III	D5, D6	19	II	B2			
			23	III	D12			
			27	II	A12			
			30	III	A10			
			32	II	B8			
			34	I	C1			
			35	II	B12			
			38	II	C8			
			39	III	A6			

TABLE VI.   TERMINAL BOARD CONNECTIONS FOR MAGNET III VOLTAGE LEADS (Cont.)

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
			40	III	B10			
			-E·coil	III	C1			
			-E·coil	III	C2			
			MR·coil	II	B7, C7			

TABLE VII. TERMINAL BOARD CONNECTIONS FOR MAGNET IV VOLTAGE LEADS

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
+E·coil	III	D11	+E·coil	III	C10	+E·coil	III	D1
+E·coil	III	C11	+E·coil	III	C12	+E·coil	III	A4
1	III	B3	1	III	A11	2	II	D6
2	I	D6	2	I	C2	3	III	A11
3	III	D6	4	I	D2	5	III	B7
4	I	B7	5	II	B11	8	II	D11
5	II	A2	6	III	D3	9	II	C6
6	II	D4	7	III	A8	12	III	D10
7	III	D12	8	II	B8	14	I	A4
8	II	D9	10	II	D2	16	II	B9
9	I	B9	12	I	C7	18	II	C12
10	I	C6	13	III	D5	19	II	D12
12	III	C8	14	I	B3	21	III	C6
14	II	B3	15	III	D7	center contact	II	D1
16	III	A3	16	I	D9			
17	III	B8	18	II	C1	25	I	C8
18	II	B10	19	I	D10	27	I	D1
19	II	A5	22	I	A10	28	I	A9
20	II	A4	23	III	B11	29	III	B6
21	III	A3	24	II	C4	31	III	A10
22	I	D11	center contact	III	A5	32	II	C9

TABLE VII.   TERMINAL BOARD CONNECTIONS FOR MAGNET IV VOLTAGE LEADS (Cont.)

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
23	III	B1				34	I	D12
24	I	D5	center contact	III	A6	36	I	B8
26	II	B5				38	II	B12
28	II	C10	25	I	C12	39	I	C1
29	II	B4	27	III	A7	42	I	B4
30	II	B2	28	I	A1	43	I	C3
31	II	C3	29	III	C5	44	I	C4
			30	I	C9	45	I	B1
			31	II	C11			
32	II	C4	32	II	A1	46	I	D4
center contact	III	B9	33	II	A8	$-$E·coil	III	C3
			34	I	A12	$-$E·coil	III	A2
center contact	III	A9	35	III	C9	MR·coil	I	D7, D8
			36	I	A3			
33	III	A1	37	III	D8			
34	I	A5	38	I	A11			
35	II	C2	39	II	A9			
36	II	C5	40	III	B2			
38	I	C10	41	II	A12			
39	III	A5	42	II	A3			
40	I	C5	43	I	A6			

TABLE VII.   TERMINAL BOARD CONNECTIONS FOR MAGNET IV VOLTAGE LEADS (Cont.)

MODULE A			MODULE B			MODULE C		
Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal	Voltage Lead	Terminal Board	Terminal
41	III	C1	44	I	A7			
42	III	D4	45	I	B6			
44	II	B1	47	I	B2			
45	II	D5	48	III	C2			
46	II	D10	49	I	A2			
47	I	C11	52	I	A8			
49	II	A10	53	III	B10			
50	III	C7	54	I	B10			
51	I	D3	55	III	D9			
52	II	D3	−E·coil	III	B4			
53	I	A5	−E·coil	III	C4			
54	III	D2	MR·coil	I	B11, B12			
56	II	B6						
58	II	A6						
59	II	C7						
64	II	A7						
66	II	B7						
−E·coil	III	B12						
−E·coil	III	A12						
MR·coil	II	D7, D8						

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coding tags on these voltage leads were removed. Voltage leads now can be iden-
tified by their terminal board connections, as shown in Tables IV through VII.

The connection tables show that some modules contain a "center contact"
point. This point refers to a central portion of the windings at which a
current contact initially was planned to provide flexibility in hookup. This
extra contact was eliminated later for simplicity, and in no case is the cen-
ter contact used or brought out to any terminal board. Voltage leads at the
outer contact are designated as -E·coil. Only one +E·coil (inner) and one
-E·coil (outer) lead usually are brought out from the Dewar to monitor the
voltage across a module and to regulate the power supply. Pins designated
"Mr·Coil" provide electrical connections to a magnetoresistive coil wound on
the inner diameter of the modules. The Mr·coils provide signals related to
local magnetic fields. The remaining leads will be used only to help locate
trouble areas.

The dots above the module designations in the headings of the tables refer
to small holes drilled in each module. The dots (and holes) are a code to
identify a particular module. These designations are shown also in Table I.

C. OUTSIDE CONNECTIONS

Current connections to the outside world are made at each magnet location
by interconnecting the 0.64-cm-square bus bars from the terminal board to
strips of a copper-superconductor combination that either come down from con-
nections at the Dewar top or from other magnets. The Dewar top connection
then can be made to the power supplies, as illustrated in Figure 14. Voltage
and diagnostic connections are made by interconnecting a cable coming through
the Dewar top directly to the magnet terminal boards.

D. POWER SUPPLY

The power supply system is the same system that was supplied for the 14-
Tesla, 15-cm-bore magnet under contract NAS 3-7101.[7,8] The operation and

7. Superconductive Magnet System, 14-Tesla, 15-Cm-Bore, Contract NAS 3-7101,
   NASA Contractor Report NASA CR-1260, January 1969.

8. Contract NAS 3-7101, Operation and Maintenance Technical Manual,
   August 1967.
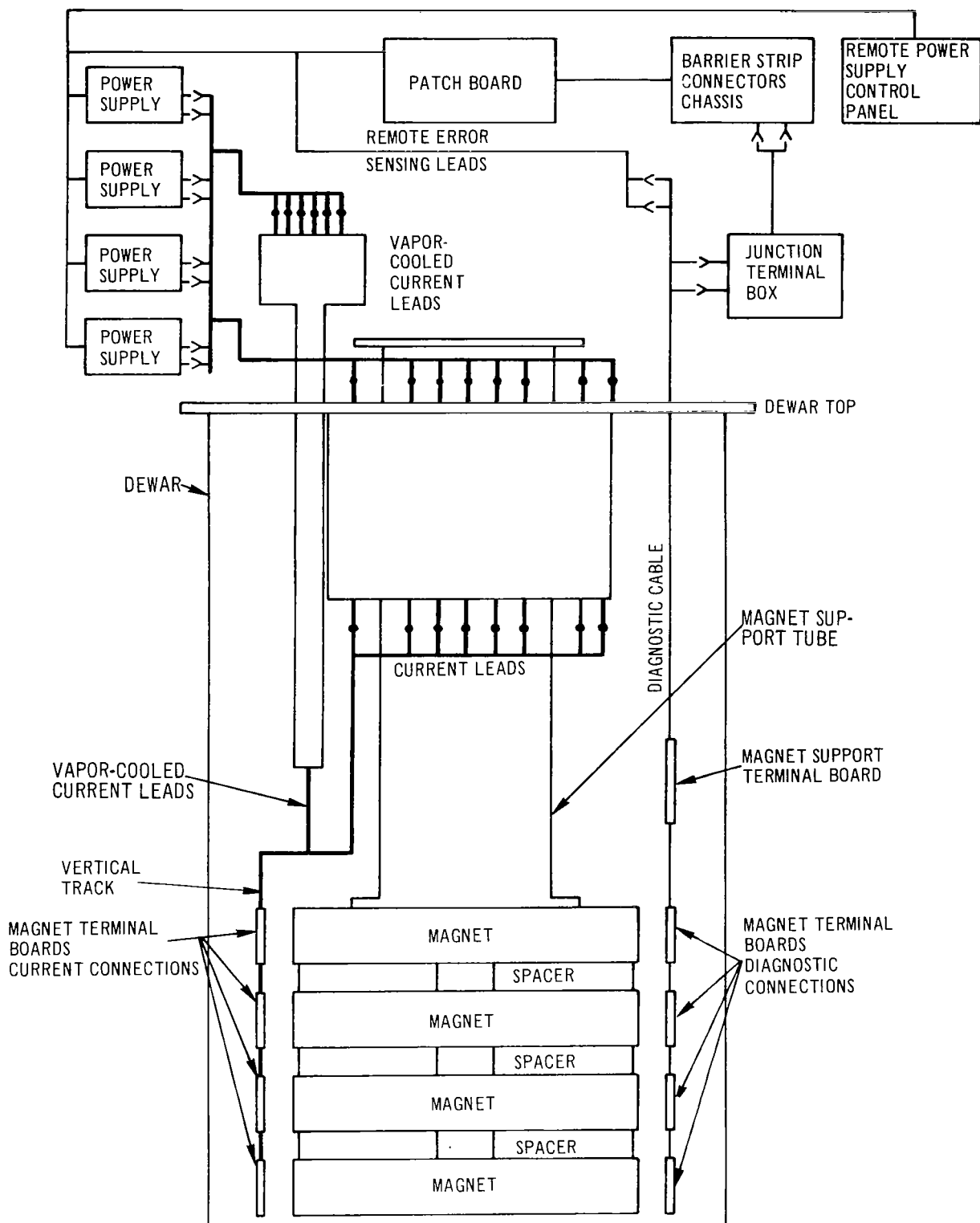
Figure 14. Cabling Diagram

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maintenance technical manual[8] identifies the junctions and barrier-strip connectors referenced in Figure 14.

SECTION IV
TEST RESULTS

A. GENERAL DISCUSSION

The highest field developed by the complete assembly of four magnets was
5.9 Teslas; the design objective of 7.2 Teslas was not achieved. The purpose
of this section is to describe salient features of the considerable test pro-
gram and to analyze the results in the amount of detail necessary to extract
knowledgeable conclusions for the benefit of others attempting similar under-
takings.

This project should be placed into its proper perspective with respect to
the state of the art of superconductive magnets from the time of conception
until recent final testing. The objective 7.2-Tesla magnet, which was to be
part of a plasma containment system, was the result of a logical series of
study and hardware efforts founded by NASA and RCA. This sequence involved
magnets ranging from small test coils to the 15-cm-bore, 14-Tesla magnet begun
in early 1965 and tested successfully in 1967. The essence of the development
was to attempt to achieve very high current densities in the coil-winding
volumes at high magnetic fields.

As magnets became larger, with accompanying higher degradations of coil
critical currents, it became necessary to dilute the windings with heavier
stabilizing silver or copper coatings on the superconductor. The design
criteria for the present contract, which started in mid-1965, were based upon
the criteria for the 14-Tesla magnet started earlier that year. By the time
that earliest test results on the 15-cm-bore magnet became available, con-
struction already had begun on the 50-cm magnets. At that time, there were
indications that degradation would be more of a problem than was anticipated
originally, and means to alleviate this effect in the 50-cm magnet were con-
sidered.

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It was recognized fully that the problem of degradation could be solved by additional stabilizing means on the ribbon (e.g., additional copper and liquid helium access), but there was no assurance that the necessary current density could be achieved. Because of space limitations, additional stabilization was impossible without a major change in design. Other techniques were used to attempt to improve stability without causing large perturbations in the project.

The first technique was to change the method of winding fabrication to include the use of high-resistance (phosphor-bronze) shorting strips in place of copper. This approach resulted from tests at RCA, which showed that the protective shunting effect of copper in large magnets was accompanied by an adverse degrading effect, which was attributed to excessive heating in the windings. Excessively long charging times were required to reduce this heating of the copper. The single module already wound with copper shorting strips was rewound, therefore, using phosphor-bronze, and subsequent fabrication of the remainder of the magnet followed accordingly.

The second technique, suggested by NASA personnel, was to use superfluid helium for improved cooling. This approach required modification of the test techniques but did not require a change in fabrication.

A third improvement was instituted on one of the four magnets by cladding the ribbon with copper, instead of the silver plating. Tests on small coils had indicated that the lower resistivity and the higher heat capacity of the copper-solder combination would yield current densities at least equal to those achieved with the silver-plated material, with the additional benefit of improved charging characteristics.

The following data are presented as a summary of the tests. Analysis of the data and conclusions therefrom also are included.

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The term "pumped conditions" is used in subsequent paragraphs. This term refers to the conditions under which pressure in the Dewar was reduced to some pressure below atmospheric pressure to reduce the helium bath temperature.

B. TEST SUMMARY

Forty-six separate tests were conducted on modules, magnets, and combinations of magnets. Detailed data are available at NASA in the form of strip-chart plots, which comprise a voluminous collection that is not included in this report. Table VIII, however, contains a summary of the approximate currents and magnetic fields developed during each test. In most cases, tests were designated for convenience of identification at the time of testing. These tests are included in Table VIII as actual test number (ATN) to permit cross referencing to the strip charts and data sheets. Because ATN's are not always distinguishable except by inclusion of the test data, a report test number (RTN) was added to Table VIII to facilitate discussion within this report. All subsequent references to tests, therefore, will be to the RTN in the first column of Table VIII.

At the earlier dates, modules sometimes were tested independent of any magnet configuration and were not associated at that time with any other modules. Table VIII identifies independent tests of modules alone by A, B, or C and a number corresponding to the code of the drilled holes in the flanges (e.g., module B-3 is a B module with three coding holes). The magnet that eventually ended up containing a given module can be determined from Table I, which relates the magnet locations of all modules. Table VIII, therefore, will contain either the magnet number or the module number.

The power supply current at normalcy in each module or group of modules is given in Table VIII along with an estimated current. Power supply current was read directly from chart readings of calibrated shunts. Estimated current was an approximation obtained by employing best judgement and using values of the measured developed central field (B_o) and the approximate Teslas/ampere ratings of the modules and magnets. Differences between power supply currents and actual coil currents are due to the large inductances of the windings,

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TABLE VIII. SUMMARY OF TEST DATA

Report Test No.	Actual Test No.	Module/ Magnet Desig.	Test Date	Power Supply Current at Module (A)			Estimated Current in Module* (A)			Measured Field (T)	Field Factor	Temp. at Normalcy (^{O}K)	Normalcy
				A	B	C	A	B	C				
1	1	A-2	3/30/67	98.0	–	–	–	–	–	–	–	4.2	Forced
2	1	A-4	3/31/67	98.0	–	–	–	–	–	–	–	4.2	Yes
3	2	A-4	3/31/67	87.0	–	–	–	–	–	–	–	4.2	Yes
4	2	A-2	3/31/67	98.0	–	–	–	–	–	–	–	4.2	No
5	3	A-2	3/31/67	92.0	–	–	–	–	–	–	–	4.2	Yes
6	4	A-2	3/31/67	108.0	–	–	–	–	–	–	–	4.2	Yes
7	3	A-4	3/31/67	85.0	–	–	–	–	–	–	–	4.2	Forced
8	1	III'	8/15/67	54.0	54.0	54.0	32.4	32.4	32.4	1.5	0.60	4.2	No
9	2	III'	8/15/67	0.0	0.0	10.0	0.0	0.0	2.0	–	–	4.2	No
10	3	III'	8/16/67	0.0	10.0	0.0	0.0	2.0	0.0	–	–	4.2	No
11	4	III'	8/16/67	46.0	0.0	0.0	–	0.0	0.0	–	–	4.2	No
12	5	III'	8/16/67	0.0	54.0	0.0	0.0	–	0.0	–	–	4.2	No
13	6	III'	8/16/67	0.0	0.0	52.0	0.0	0.0	52.0	–	–	4.2	No
14	7	III'	8/16/67	51.0	49.0	52.0	38.0	14.0	43.0	1.57	0.71	4.2	No
15	8	III'	8/17/67	95.0	0.0	0.0	40.0	0.0	0.0	0.8	0.42	4.2	Yes
16	9	III'	8/17/67	0.0	0.0	80.0	0.0	0.0	36.0	0.4	0.45	4.2	Yes
17	10	III'	8/17/67	70.0	50.0	0.0	38.0	50.0	0.0	1.53	0.70	4.2	Yes
18	II-1	II	9/05/67	80.0	76.0	80.0	59.0	56.0	59.0	2.5	0.73	4.2	No
19	II-2	II	9/06/67	40.0	41.0	88.0	39.5	40.5	82.0	2.2	0.96	4.2	Yes
20	II-3	II	9/06/67	40.0	80.0	71.0	40.0	77.0	70.5	2.6	0.97	4.2	Yes
21**	II-4	II	9/07/67	90.0	70.0	71.0	88.0	70.0	71.0	3.4	0.98	4.2	Yes
22	II-5	II	9/07/67	85.0	70.0	73.0	81.2	67.0	69.6	3.23	0.95	4.2	Yes
23	III-11	A'-3	9/08/67	87.0	–	–	68.0	–	–	1.45	0.83	4.2	Yes
24	II-1P	II	10/10/67	65.0	56.0	58.0	48.5	42.0	43.5	1.97	0.75	2.13	Yes
25**	II-2P	II	10/11/67	102.0	101.0	104.0	100.0	100.0	100.0	4.4	0.98	1.92	Yes

TABLE VIII.   SUMMARY OF TEST DATA (Cont.)

Report Test No.	Actual Test No.	Module/ Magnet Desig.	Test Date	Power Supply Current at Module (A)			Estimated Current in Module* (A)			Measured Field (T)	Field Factor	Temp. at Normalcy (°K)	Normalcy
				A	B	C	A	B	C				
26	III-1	III	11/27/67	40.0	80.0	0.0	40.0	68.0	0.0	1.82	0.87	4.2	Yes
27	III-2	III	11/27/67	91.0	0.0	0.0	75.0	0.0	0.0	1.5	0.83	4.2	Yes
28**	III-3	III	11/28/67	62.0	58.0	52.0	52.0	48.0	42.0	2.26	0.83	4.2	Yes
29	III-4	III	11/29/67	27.0	32.0	68.0	24.0	27.0	58.0	1.55	0.85	1.85	Yes
30**	III-5	III	11/30/67	95.0	80.0	51.5	92.0	78.0	50.0	3.64	0.98	1.92	Yes
31	I-1	I	6/03/68	93.0	0.0	0.0	65.0	0.0	0.0	1.36	0.70	4.2	Yes
32	I-2	I	6/04/68	40.0	82.5	0.0	31.0	44.0	0.0	1.34	0.63	4.2	Yes
33	I-3	I	6/04/68	40.0	40.0	80.0	34.0	23.0	46.0	1.57	0.67	4.2	Yes
34	I-4	I	6/04/68	70.0	52.0	50.0	57.0	33.0	28.0	2.00	0.71	4.2	Yes
35	I-5	I	6/05/68	83.0	71.5	90.0	76.0	63.0	60.0	3.20	0.86	1.9	Yes
36	IV-1	IV	6/05/68	80.0	0.0	0.0	56.0	0.0	0.0	1.10	0.69	4.2	Yes
37	IV-2	IV	6/05/68	40.0	100.0	0.0	39.0	77.0	0.0	2.0	0.80	4.2	Yes
38	IV-3	IV	6/06/68	40.0	40.0	80.0	37.0	30.0	40.0	1.6	0.65	4.2	Yes
39	IV-4	IV	6/14/68	73.5	93.0	78.5	70.0	82.0	41.0	3.17	0.84	1.85	Yes
40A	I, IV-1	I IV	6/15/68	78.0 75.0	78.0 75.0	78.0 75.0				5.20	0.88	1.78	Yes
40B	I, IV-2	I IV	6/16/68	49.0 52.5	49.0 52.5	49.0 52.5				3.28	0.84	4.2	Yes
40C**	I, IV-3	I IV	6/17/68	84.0 84.0	84.0 84.0	80.0 80.0				5.8	0.91	1.80	Yes
40D**	I, IV-4	I IV	6/18/68	71.5 71.5	71.5 71.5	71.5 71.5				5.0	0.91	4.2	Yes
41	1	I IV II III	11/4/68	62.0 62.0 21.0 21.0	62.0 62.0 21.0 21.0	62.0 62.0 21.0 21.0				3.95	0.76	2.3	Yes

TABLE VIII. SUMMARY OF TEST DATA (Cont.)

Report Test No.	Actual Test No.	Module/ Magnet Desig.	Test Date	Power Supply Current at Module (A)			Estimated Current in Module* (A)			Measured Field (T)	Field Factor	Temp. at Normalcy ($^{\circ}$K)	Normalcy
				A	B	C	A	B	C				
42	2	I	11/06/68	59.0	59.0	59.0				4.75	0.93	3.0	Yes
		IV		59.0	59.0	59.0							
		II		32.0	32.0	32.0							
		III		27.0	27.0	27.0							
43**	3	I	11/07/68	77.5	77.5	77.5				5.93	0.90	1.8	Yes
		IV		77.5	77.5	77.5							
		II		33.0	33.0	33.0							
		III		30.0	30.0	30.0							
44	4	I	11/12/68	60.0	60.0	54.0				5.1	0.93	1.8	Yes
		IV		60.0	60.0	54.0							
		II		65.0	65.0	65.0							
		III		44.0	44.0	16.0							
45	5	I	11/13/68	73.8	73.8	66.0				5.87	0.91	1.76	Yes
		IV		73.8	73.8	66.0							
		II		43.7	43.7	43.7							
		III		38.6	38.6	24.0							
46	6	I	11/14/68	70.5	70.5	67.5				4.65	0.80	1.85	Yes
		IV		70.5	70.5	67.5							
		II		4.5	4.5	4.5							
		III		3.1	3.1	4.0							

*Close coupling among magnets prevented estimating module currents for tests 40 through 46.

**Described in more detail in text.

which force significant portions of the applied current into the shorting strips. The strong inductive coupling between modules and magnets precluded knowing the instantaneous relationship between applied and actual currents. Reasonable estimates of actual module currents were obtained only by back-calculation from the developed central field. The column in Table VIII designated "Field Factor" gives the ratio of measured field over the field that would have been attained if all power supply current had been creating the magnetic field. Where charging was very slow, this field factor approaches unity. The last column indicates the temperature of the helium bath at normalcy, as determined by vapor-pressure readings when not at atmospheric pressure.

In some cases, the tests were conducted to check magnet parameters (e.g., effective resistance of shorting strips) and instrumentation for scale and polarity, rather than to determine critical currents. When the critical current of a single module in a magnet was to be determined, the currents of the other modules often were kept to a very low value. Normalcy sometimes occurred while transferring helium and changing the temperature. The following paragraphs will explain briefly the more important reasons for which the tests were conducted so as to make the results more meaningful.

1. TESTS 1 THROUGH 7

Tests 1 through 7 were performed to obtain preliminary data on the first available modules and to establish test procedures for the remainder of the program. The modules in this group of tests were not tested for magnetic field and true critical current. Because data of any significance are not available, this group of tests will not be discussed in further detail.

2. TESTS 8 THROUGH 14

Magnet III was the first complete assembly of three modules available for testing. As with tests 1 through 7, this group of tests represents an effort to obtain initial data as a guide to later, more complete magnet tests. The large inductance of a single magnet, coupled with the shorting of layers, resulted in less response between applied current and developed field than

was anticipated originally. None of these tests were taken to normalcy; they mostly involved attempts to analyze current and field characteristics as a result of specific and varied voltage changes.

Test 14 was conducted with periodic reductions of module voltages to zero to observe the approach to time-equilibrium currents in the windings. It became obvious at this point that quite long periods of time (hours) would be required under conditions of "current hold" before transport current in the windings would approximate that from the power supply.

3. TESTS 15 THROUGH 17

Having obtained general characteristics of the system in tests 8 through 14, tests 15 through 17 were conducted to obtain estimated values of transport current for magnet III. In test 15, modules B and C were unpowered and module A was brought up to normalcy. In test 16, A and B were kept at zero while C was brought up to normalcy. As can be seen from Table VIII, less than one-half of the power supply current can be considered as actually developing a centroid field. It was impossible to establish what part of the remaining module current also was transport current but, due to reversed induction in the unpowered modules, had its field contribution negated.

Experience with many superconductive magnets has shown the possibility of field stabilization to decrease degradation; accordingly, test 17 was run to subject module A to a background field from B. The estimated critical current of A, however, showed little difference, probably due to the fact that only part of the windings of A were subject to any significant background field due to the small cross section of the B windings.

4. TESTS 18 THROUGH 22

This test group comprises $4.2^{\circ}K$ tests for magnet II, which is the only magnet wound with the more stable copper-clad ribbon. Test 18 was conducted specifically to obtain current and field responses to step-function voltage inputs for later computer analysis.[9] The critical current of module C was

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9. Mr. U. Christensen, Princeton University, was retained to do these calculations. The complexity and nonlinearity of the system, however, obviated meaningful computed results.

checked in test 19 by holding A and B at low current levels (to reduce some of the diamagnetic shielding). A similar procedure in tests 20 and 21 gave an estimated I_c for B and A. Test 22 was an attempt to attain these estimated critical currents simultaneously. The resulting currents were close to those estimated from the results of previous tests. Test 21 is described further in Paragraph IV.C.2.a.

5. TEST 23

When magnet III' was dismounted in preparation for mounting magnet II, some possible shifting of the windings was noted (see Figure 11). There was some question at the time magnet III' was tested as to the detrimental effects of the apparently excessive shorting of module B'-3; therefore, the opportunity was taken to test module A'-3 alone in test 23. The resulting 68 amperes seemed to indicate an improvement of over 20 amperes (see the results of tests 15 and 17 in Table VIII) when A-3 had no adjacent modules.

6. TESTS 24 AND 25

Recognizing that the stability attained by operating below the lambda point would be necessary for the magnet assembly to achieve specifications, tests 24 and 25 were conducted on magnet II in a pumped Dewar. The magnet went normal at 1.97 Teslas in test 24; this low value was thought to be due to the temperature having been very close to the lambda point. The temperature was reduced to below $2^{\circ}K$ in test 25 (see Paragraph IV.C.2.b), and all modules attained a power supply current of over 100 amperes. The resulting centroid field of 4.4 Teslas represents a 30-percent improvement over the field achieved by this magnet at $4.2^{\circ}K$.

7. TESTS 26 THROUGH 30

This test series was a retesting of magnet III' after repairing some shifted outer layers of modules A'-3 and C'-4 and after completely rewinding module B'-3. (The repaired modules and magnets are designated by omitting the prime.) Module B was energized to normalcy in test 26, with A held at 40 amperes to reduce shielding. This module B exhibited a faster reaction time than module B', confirming that the problem with B' had been one of

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excessive shorting. Module A was tested for critical current in test 27; the resulting value was 30 amperes higher than that obtained during previous testing in the presence of the excessively shorted B' module. To get a $4.2^{O}K$ evaluation of this reworked magnet, all three modules were powered simultaneously in test 28 (see Paragraph IV.C.1.a), with current ratios as indicated from previous tests. Magnet IV, however, did not develop the expected currents.

Using the experience obtained from testing magnet III at $4.2^{O}K$, tests 29 and 30 were conducted at pumped conditions. In test 29, normalcy occurred at a lower value than had been expected. Data indicated that this normalcy was due to module C being brought up to too high a current. In test 30 (see Paragraph IV.C.1.b), therefore, C was held below its previously estimated value. The field, in this case, went to 3.64 Teslas, which represents the performance of a magnet wound with silver-plated ribbon at pumped conditions. This value can be compared with the 4.4 Teslas achieved with the copper-clad version (test 25).

8. TESTS 31 THROUGH 35

Magnets I and IV were mounted on the same holder but were separated by 47.7 cm to approximate individual magnet tests. The results of tests 31 through 35 are for magnet I. Test 31 evaluated module A, test 32 evaluated module B, and test 33 evaluated module C. All modules were powered in test 34 to obtain magnet performance at $4.2^{O}K$; the results were slightly lower than for magnet III, which also is wound with silver-plated Nb_3Sn ribbon. The magnet was tested under pumped conditions in test 35, during which 3.2 Teslas were developed at normalcy. The magnitude of this field generally was the same as for magnet III (test 30).

9. TESTS 36 THROUGH 39

This test series for magnet IV was similar to tests 31 through 35. Module currents were established in tests 36 through 38 at $4.2^{O}K$; a final test was performed under pumped conditions in test 39. A 3.18-Tesla field was attained.

10. TESTS 40A THROUGH 40D

Because of similarities in critical fields and response times, magnets I and IV were chosen to be the center pair of magnets in the final assembly. The magnets were assembled, with separation by compression members, and were tested as a two-magnet system. Four tests were conducted at 4.2°K and under pumped conditions. The objectives were to assess performance characteristics and test procedures for a two-magnet system.

In test 40A, each magnet was powered with its modules in series by a separate power supply. Power supply current to magnet IV lagged slightly that of magnet I. This test was performed at reduced temperatures. Test 40B was similar to test 40A, but was performed at 4.2°K to evaluate improvement due to pumping. Test 40A had indicated that the C modules probably were limiting the results. In test 40C, the A and B modules of both magnets were powered with one power supply, while the C modules were powered with another. The resulting field of 5.8 Teslas was very close to the maximum field calculated from the estimated critical currents obtained in previous tests. Tests 40C and 40D are described further in Paragraphs IV.C.3.a and IV.C.3.b, respectively.

11. TESTS 41 THROUGH 46

Tests 41 through 46 were conducted at reduced temperatures on the complete four-magnet assembly. Magnets I and IV were retained as the central pair, because they already had been tested together and each magnet separately had given similar results. Tests 41 and 42 were aborted due to premature normalcy during helium transfer, when the temperature increased through the lambda point. Test 43 (see Paragraph IV.C.4) gave the highest field of all tests, but the resulting 5.93 Teslas was short of the specified 7.2 Teslas.

Because of the possibility that module C of magnet III had caused a premature normalcy of the four-magnet assembly in test 43, test 44 was conducted with a separate (additional) power supply on this module. Even with only 15 amperes in III-C, however, normalcy occurred at 5.87 Teslas.

There were no apparent reasons as to why the complete magnet assembly had reached only 5.93 Teslas when the center magnet pair alone had reached

5.8 Teslas. The center pair may have been damaged during the four-magnet tests. Test 46 essentially was a retest of magnets I and IV, but with the end magnets held at very low currents. The center pair went normal while developing a field of 4.65 Teslas (essentially nothing being contributed by the end magnets). This result indicated that either some damage had occurred to magnets I and IV or the presence of the two end magnets was sufficient to contribute to degradation of I and IV. The scope of the contract did not permit further investigation into this matter.

C. TEST ANALYSES

The test summaries contained in Paragraph IV.B indicate the general explor-atory nature of the earlier tests. Considerable exploration was necessary, because the high degree of inductive coupling among modules and magnets and the shorting of turns with phosphor-bronze strips made difficult the determin-ation of true critical currents. In the case of a test on a single magnet composed of three modules, the contribution of module C to the centroid field always was difficult to assess due to the large shielding effects of modules A and B. The same condition was true, to a lesser degree, for B due to the shielding of A. Values of actual transport currents were estimated, where possible, from the experience of all tests involving individual modules and combinations, in which data were obtained by periodic observations of module currents at zero voltage or by long "hold" times at constant current to reduce the shunting current in the shorting strips. Because a complete discussion of the details of each manipulation on all 46 tests is not feasible and would contribute little additional technical information, the following paragraphs contain analyses of only representative tests performed in the latter portion of the program. The tests that have been selected for this purpose are as follows:

NOTE

"Pumped conditions" are the conditions under which pressure in the Dewar was reduced to some pressure below atmos-pheric pressure to reduce the helium bath temperature.

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Magnet	Test No.
III (silver-plated version)	28 (4.2°K)
	30 (pumped conditions)
II (copper-clad version)	21 (4.2°K)
	25 (pumped conditions)
I and IV (silver-plated version)	40C (pumped conditions)
	40D (pumped conditions followed by elevation to 4.2°K)
I through IV assembled	43 (pumped conditions)

1. MAGNET III

Magnet III' (the prime refers to a version before partial rewinding) was evaluated in tests 8 through 17 and 23. Many of these tests were exploratory and were performed in an attempt to understand how meaningful tests could be conducted when interpretation of the results was complicated by the large inductive interactions among modules and by the masking effect of the shorting strips. It was decided eventually that the shorting of module B' was excessive, compared to A' and C'. All modules also showed shifts of the outer layers (see Figure 11). These few shifted layers were rewound on A' and C', and module B' was completely rewound, substituting new ribbon where necessary.

Tests 26 through 28 were performed to evaluate magnet III (the rewound version). Test 26 showed a marked improvement in the time constant of the B results over the B' results. Test 27 was a test of A to determine whether the long time constant on B' had an adverse effect on A'. Because the difference between A and A' (and C and C') was only the rewinding of a few outer layers, they therefore are considered to be essentially unaltered. Because the true current of module A was over 74 amperes, as compared with the 40 amperes estimated in test 15 for A', it was assumed that part of this improvement was due to reducing the adverse effect of the overly shorted B'.

A logical follow-on after test 27 would have been a test of module C similar to test 26. Experience had shown, however, that tests on the C modules always were difficult to interpret because of the large shielding effects of

the A and B modules. It was decided, therefore, to anticipate an improvement in C similar to that found in A, and test 28 was conducted under the assumption of estimated true currents of 75 amperes for A, 65 amperes for B, and 60 amperes for C.

   a. <u>Test 28 (4.2°K)</u>. Plots of module voltages, power supply currents, and central field versus time are shown in Figure 15. These plots, and subsequent similar plots, show an absence of minor perturbations in the parameters. Strip-chart recordings are available at the NASA Lewis Research Center for detailed information.

   All module potentials were set at 500 millivolts during the first 20 minutes of test 28. Initial settings are not shown in the plots, because they usually are somewhat arbitrary until definite trends are indicated. Between 20 minutes and 30 minutes, the voltages on B and C were increased to counteract the high current surge in C. Experience has shown that module C in a magnet configuration had an apparently higher ratio of shorting current to transport current than did either A or B due to the higher effective inductance. Currents in the C modules in these tests and similar tests were kept low with minimized rates of change because of the possibility of heating within the windings.

   Voltages are juggled frequently during a test such as this to manipulate the indicated power supply currents to a ratio that best judgement indicates will result in the desired ratios of true currents. Step-function variations of 100 millivolts, such as are shown in Figure 15, produce changes in module currents of only several amperes, which is a reaction of the shorting circuits of the magnet to the voltage change. The effects of these changes on the field are almost indiscernible. A larger change of voltage, e.g., 300 millivolts, would show up within about 5 minutes as a shift in the slope of the magnetic field curve. Each change in a single module voltage produces opposing trends in the other modules. It was deduced from the data displayed by strip-chart and Visicorder recordings for test 28 that C went normal first, driving the other modules normal for a total centroid field of 2.26 Teslas.
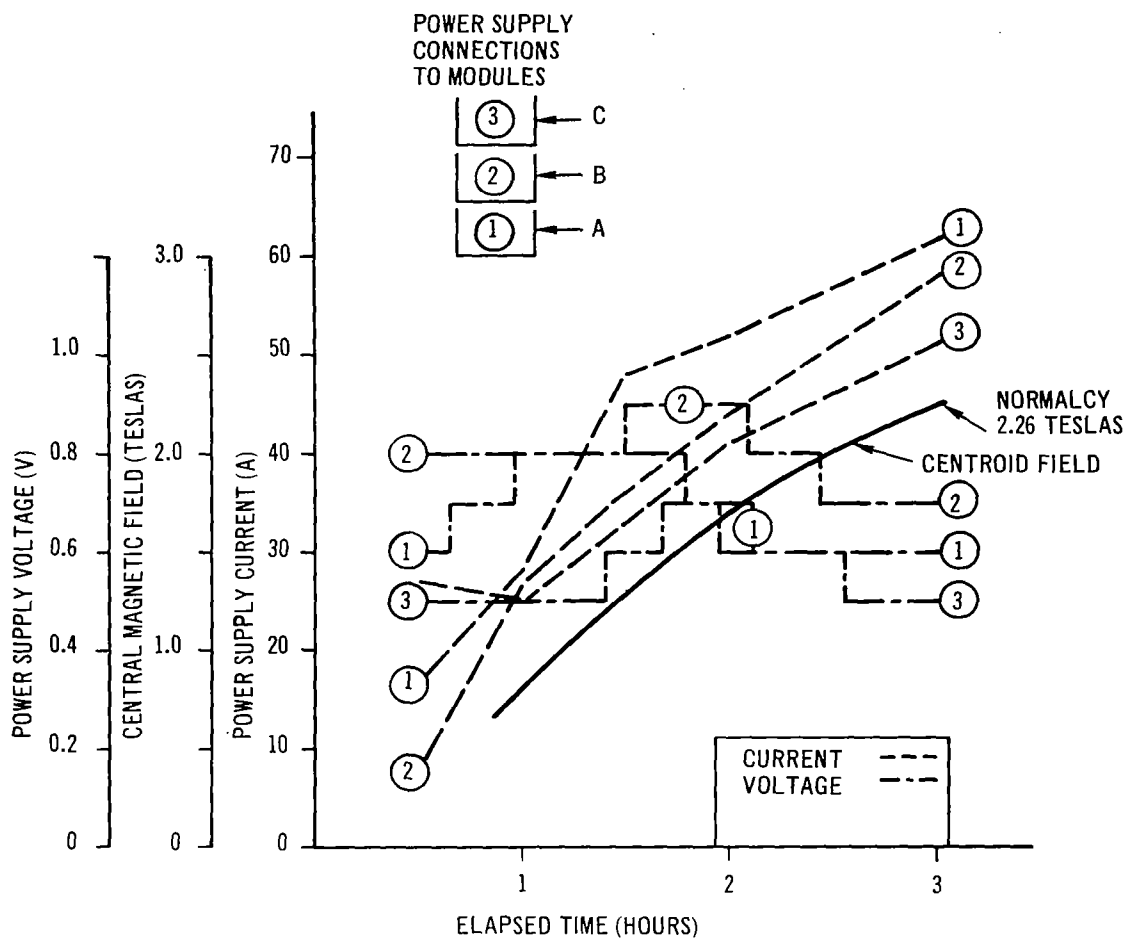
Figure 15. Magnet III, Test 28, 4.2 °K

Due to the apparently improved performances of the A and B modules in tests 26 and 27, the result of test 28 was disappointing. It is reasonable to expect that a higher field could have been achieved at 4.2°K by further manipulations of relative powering levels. Because operation at 4.2°K was considered only preliminary to operation below the lambda point, the remaining tests of magnet III (tests 29 and 30) were performed under pumped conditions.

b. <u>Test 30 (Pumped Conditions)</u>. The A and B module currents in test 29 were held low, and the C module was brought up to normalcy. This approach was used to establish a probable current for C at low temperatures. Test 30 then was conducted to use the best estimates of all three module currents.

Tests of magnet III prior to test 30 yielded estimated critical-current values for the three modules at 4.2°K. Test 30 was conducted at temperatures below the lambda point to take advantage of the improved stability of the superconductor. In the absence of individual module tests at low temperatures, it was assumed that the ratios of acceptable currents established at 4.2°K would hold also at low temperatures. To achieve the objective field value of 4 Teslas, the projected module currents should have been approximately 96 amperes for A, 81 amperes for B, and 58 amperes for C. The details of this test are given in Figure 16.

The temperature was determined by remote readings of the helium pressure within the Dewar and conversion of the readings by standard tables. It became obvious early in the test that the maximum rate at which the magnet could be powered would be determined by the requirement for minimum power dissipation to stay below the lambda point. It was not known if any particular temperature level would be optimum[10], but practicality dictated the temperatures indicated in Figure 16. The increasing heat capacity of liquid helium with temperatures approaching the lambda point presumably determined the rate that resulted in operation in the vicinity of 1.9°K. Figure 16 shows that the

10. Later temperature tests on a small magnet with Nb_3Sn ribbon were conducted at the NASA Lewis Research Center by G. Brown and E. Meyn. These tests showed that critical current increased slightly as the temperature was decreased below the lambda point.
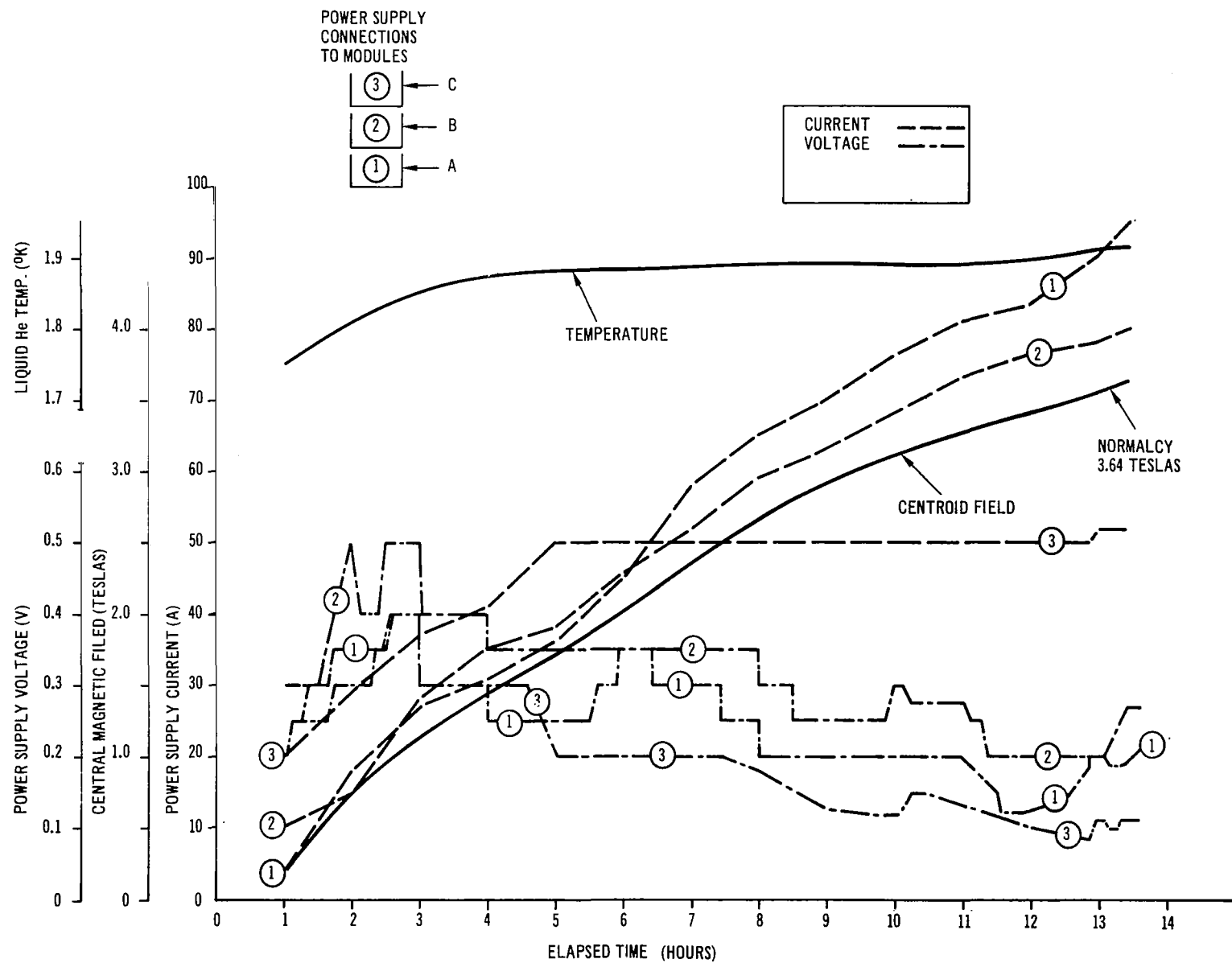
Figure 16. Magnet III, Test 30, Pumped Conditions

charging voltages had to be decreased steadily after the first 3 hours to maintain this temperature.

Because test 29 resulted in what appeared to be a limiting current of 58 amperes for module C, module C was held at about 50 amperes for the last two-thirds of the test, while A and B were charged continually until normalcy occurred. Actual currents are estimated to be 92 amperes for A, 78 amperes for B, and 50 amperes for C. These values compare to power supply currents of 95 amperes, 80 amperes, and 51.5 amperes, respectively. The long charging period of the test, determined by the requirement to maintain a given temperature, gave the advantage that very little current was shunted into the shorting strips.

The field achieved was 3.64 Teslas under pumped conditions, compared to 2.26 Teslas at 4.2°K (test 28). These values cannot be compared directly, because different powering sequences were used. It is reasonable to assume that further testing at 4.2°K would yield higher fields. The 60-percent improvement by pumping probably is higher than could be expected if the electrical parameters were more consistent. Both module B and module C showed positive voltage pips in strip-chart recordings, indicating that initial normalcy could have come from either module.

2. MAGNET II

a. _Test 21 (4.2°K)_. Plots of module voltages, power supply currents, and field versus time are shown in Figure 17. Test 21 was the last test in a series, the purpose of which was to determine best-estimate values of critical currents for each module. Tests 19 and 20 provided estimated values of 82 amperes and 77 amperes for modules C and B, respectively. Modules C and B were held at power supply currents close to 70 amperes for test 21, and A was brought to normalcy. Initial voltages on the modules of magnet II were considerably higher than were permissable for magnet III, because copper cladding offers less than one-half the resistance of the silver plating to any current that might be in the normal metal layer; therefore, less current is shunted to the shorting strips in the copper-clad version.
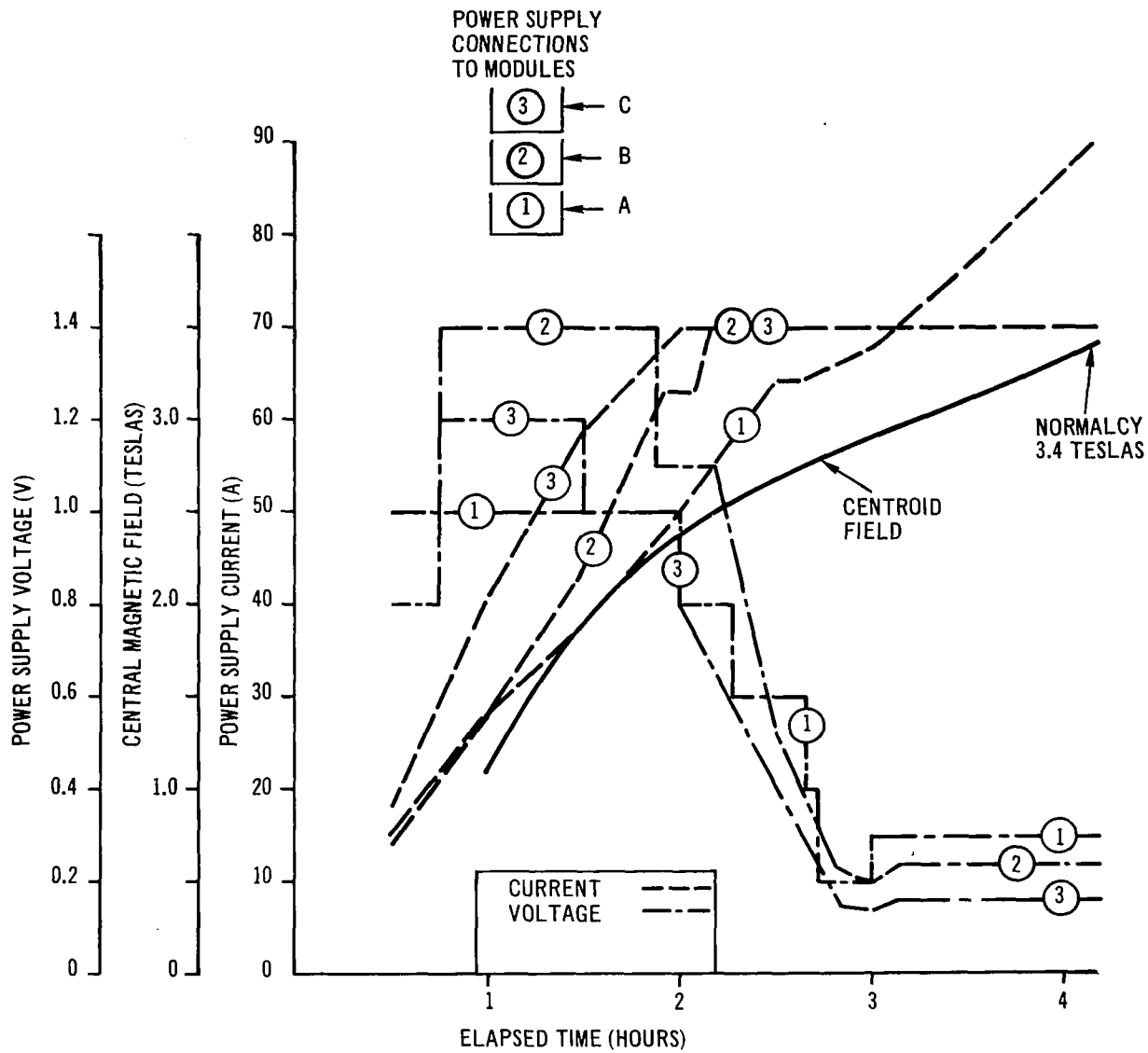
60

Figure 17. Magnet II, Test 21, 4.2°K

Normalcy occurred at 3.4 Teslas. Although this value is less than
the specification value of 4 Teslas for a single magnet, the value was a con-
siderable improvement over that obtained for magnet III. Modules B and C
probably could have been set to higher values, and it is possible that the
full field could have been achieved. The value of 3.4 Teslas was sufficient,
however, if it could be achieved in the four-magnet configuration to meet
the overall specification.

Test 21 showed that magnet II was much more stable than versions
with silver-plated ribbon. This improvement was indicated by the relatively
quick responses of modules currents to voltage changes and by the lack of
noise on Visicorder traces.

Module voltages were reduced severely during the latter part of
test 21. The purpose of this experiment was to ensure that essentially all
power supply current would be in the windings at normalcy.

b. Test 25 (Pumped Conditions). Test 25 approximately represented
the pumped-conditions counterpart of test 21. Test 25 can be compared gener-
ally to test 30 on magnet III, because both tests were performed on single
magnets under pumped conditions. Voltages and currents for test 25 are given
in Figure 18.

This test exceeded all others in terms of ease of charging, lack
of noise, and apparent stability. Module voltages were maintained between
300 and 500 millivolts throughout most of the test, and magnetic-field inten-
sity increased at a constant rate. As in most low-temperature tests, the
rate of increase was determined chiefly by the limitation on pumping rate.
Pumping rate, in turn, limited the power that could be dumped into the Dewar.
Maximum permissible charging rates, therefore, are unknown.

Normalcy occurred at 4.4 Teslas. Because this magnet exceeded
the specification for 4 Teslas, there was little doubt that a complete system
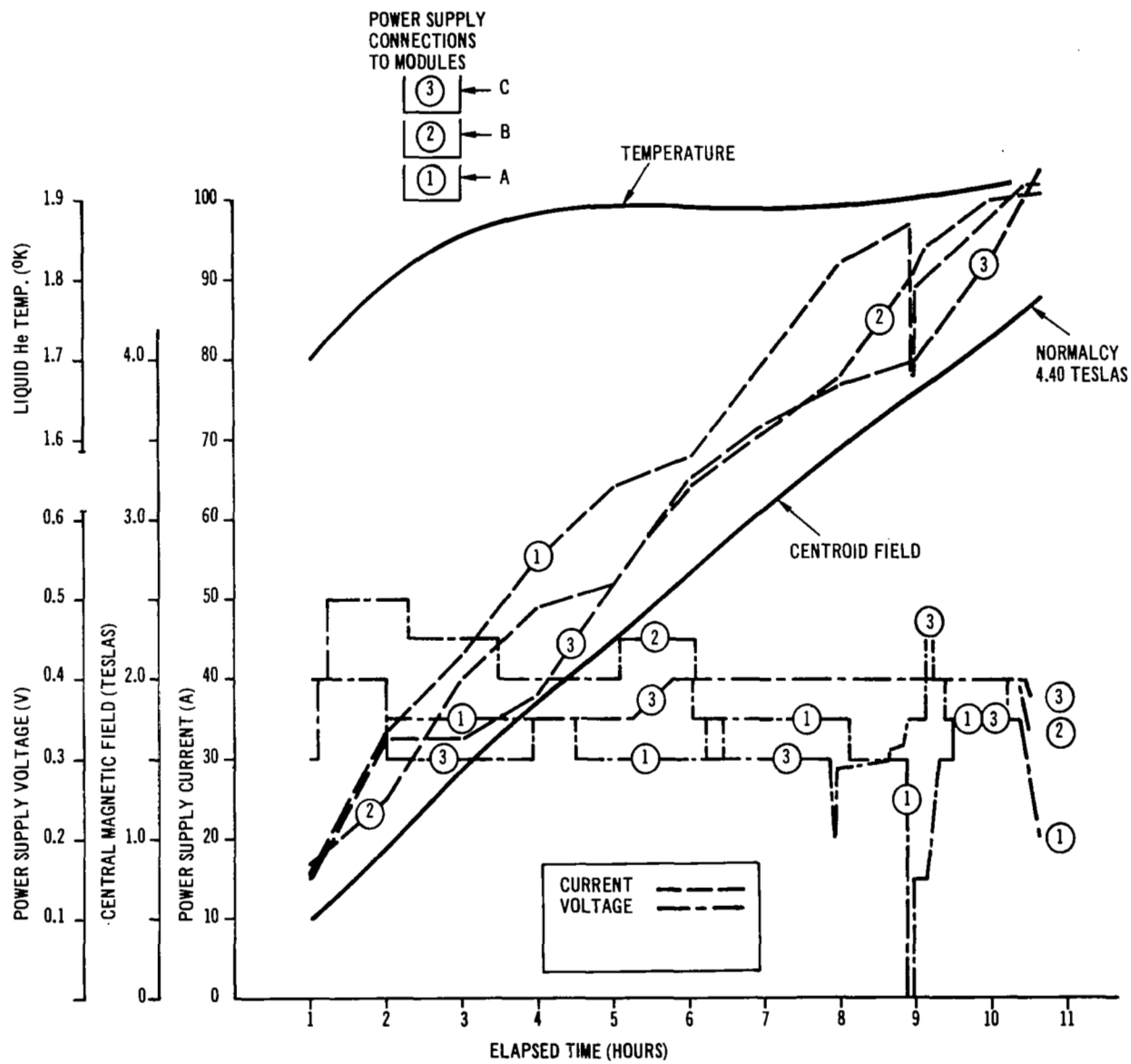of four magnets of this design would attain the required 7.2 Teslas.

Figure 18. Magnet II, Test 25, Pumped Conditions

The normalcy that occurred at the end of test 25 caused the bottom of the Dewar to collapse and magneto-form against the magnet. The Dewar manufacturer traced the cause of this problem to currents that were induced in a copper sheath around the getter in the evacuated space of the Dewar.

3. MAGNETS I AND IV

Magnets I and IV were mounted together for testing preliminary to testing the full four-magnet system. Tests 40A and 40B on combined magnets I and IV were not completed due to premature normalcy while the temperature climbed uncontrollably during helium transfer. This problem was eliminated in all subsequent tests by charging the magnet partially at 4.2° (to approximately 20 kilogauss), refilling the Dewar, and then pumping. This procedure provided a head start on the test with a sufficient volume of superfluid helium available.

a. <u>Test 40C (Pumped Conditions)</u>. Plots of module currents, power supply voltages, centroid field, and temperature versus time are shown in Figure 19. All modules A and B were connected in series to one power supply, and modules C were connected to another. Previous history on magnet I was obtained from tests 31 through 35 and on magnet IV from tests 36 through 39. Experience again had showed the relatively higher stability of modules A and B, as compared to modules C, which is the reason that modules were connected separately in test 40C.

The voltages on magnets I and IV were kept relatively constant throughout the test, although they were varied, when necessary, to limit the temperature rise of the helium bath. The voltages of both power supplies also were reduced periodically to zero to assess the level of transport current in the modules. Large inductive coupling was evident, especially in the C modules, by the large percentage of power supply current that was lost in the shorting strips upon such voltage reductions. Large inductive coupling was most prevalent during early stages of the test, when the predominantly low field values in the total volume of the magnets resulted in the highest diamagnetic current shielding.
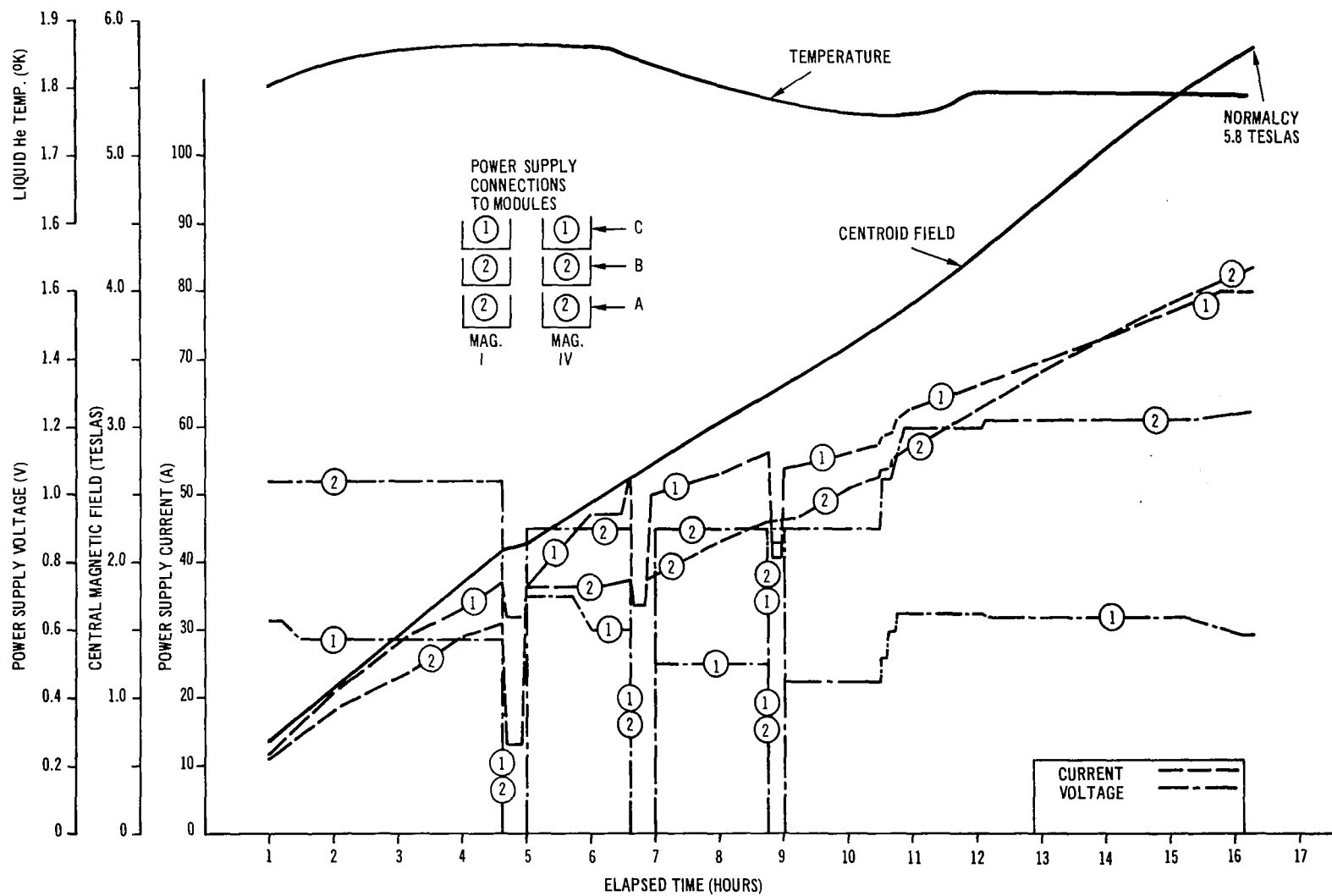
64

Figure 19. Magnets I and IV, Test 40 C, Pumped Conditions

Just before normalcy occurred, the C modules were held at 80 amperes of power supply current, and the voltage began to decay. Even with detailed Visicorder signals from many sections of the magnets, the module in which normalcy first occurred could not be determined uniquely, although it was probably one of the C modules. The 5.8-Tesla centroid field attained with these two magnets indicated that the remaining 1.4 Teslas necessary to meet the specification for 7.2 Teslas with four magnets probably would be attained.

b. Test 40D (Pumped Conditions Followed by Elevation to 4.2°K). The decision to operate the magnets at reduced temperatures was made originally when it was evident that the specified field would not be attained during operation at 4.2°K. Because previous tests had showed that operation under pumped conditions presented no great difficulties, it was decided to investigate a potential additional advantage of being able to raise the temperature back to 4.2°K once a desired field was attained. This approach meant passing through temperatures just above the lambda point, where instability is known to be greatest. Test 40D was conducted, therefore, to make this determination. The results are shown in Figure 20.

All six modules were connected in series to one power supply for simplicity. The field was raised to slightly less than 5 Teslas under pumped helium conditions. At that point, transfer of 4.2°K liquid helium was initiated carefully as a means of raising the temperature of the helium in the Dewar in a reasonably controlled manner. Magnet current was held essentially constant during this period, although minor voltage changes were made, by hand control, to minimize small but rapid field changes that occur unpredictably throughout the transfer. Such field changes resulted from power surges due to changes in the rate of cooling of current leads into the Dewar.

The field crept upward slightly during the hour required to raise the temperature to 4.2°K. Equilibrium was maintained for approximately 10 minutes at 4.2°K to verify that transition through the unstable temperature region had been made successfully. The voltage then was increased to the level that was the highest during reduced-temperature operation. Normalcy occurred after a quick rise in the field of 0.1 Tesla.
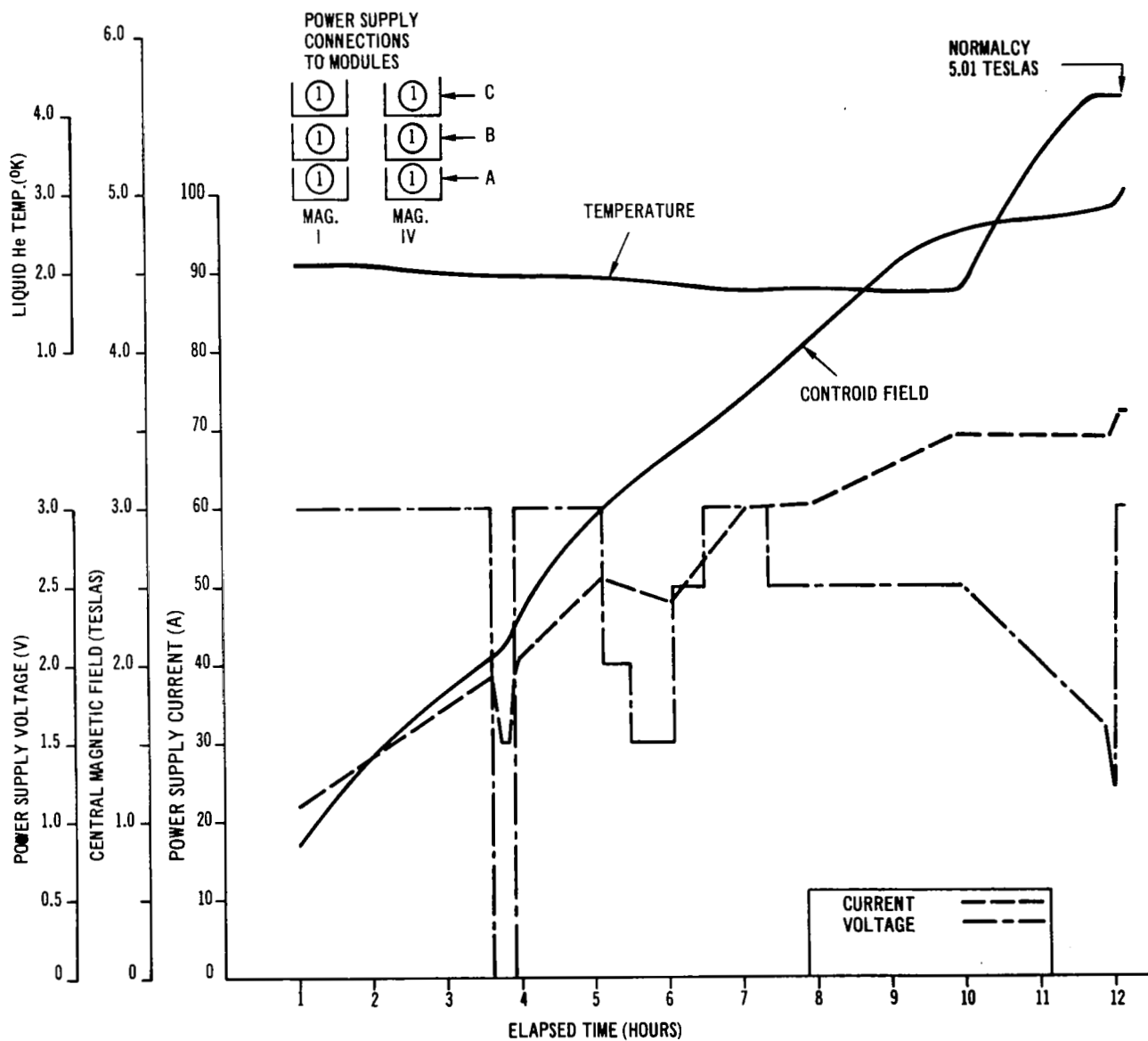
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Figure 20. Magnets I and IV, Test 40 D, Pumped Conditions Followed by Elevation to 4.2 °K

The success of a transition through an extremely unstable tempera-
ture region (immediately above the lambda point) depends upon the overall
stability of the system. The system was sufficiently stable in this case.
A similar situation occurred inadvertently at a later date with the four-mag-
net system in which the temperature rose when a helium transfer became neces-
sary. Normalcy occurred in that case.

4. FOUR-MAGNET ASSEMBLY

Four tests were conducted on the four-magnet assembly. Tests 41 and 42
were aborted, due to normalcy during transfer of helium. Test 43 was the most
successful test, achieving a field of 5.93 Teslas. The results of test 43 are
shown in Figure 21. Test 44 was an unsuccessful attempt to increase the field
from the 5.93 Teslas achieved in test 43.

The four magnets were divided into three powered sections. Center
magnets I and IV had operated well together during previous tests and, for
simplicity, were connected in series for test 43. The modules of magnet II,
at one end of the assembly, were connected in series to power supply 1. The
modules of magnet IV, at the opposite end, were connected in series to power
supply 3. Separate supplies were required for each end magnet, because magnet
II (wound with copper-clad ribbon and fewer turns) required a higher current
to produce a given field than magnet III (wound with silver-plated ribbon).

The objectives of test 43 were to develop a slight field from the two
end magnets and to establish whether the fields of the two end magnets influence
adversely center magnets I and IV, which had shown good results in test 40C.

After initial charging at 4.2°K and then transferring and pumping to
get below the lambda point, the two end magnets were held constant at 30 and
33 amperes (giving equivalent field contributions). This low value was thought
to assure that if any normalcy occurred, it would originate in the center
two magnets for which previous data existed as a pair. It is not certain that
magnet III was quiescent, as far as influencing the eventual normalcy, because
the module voltages were extremely noisy during the test. Test 44, which
followed, was conducted to keep module C of magnet III at only 16 amperes to
reduce further any effect of noise; there was no noticable improvement.

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Figure 21 Complete Magnet Assembly Test 43, Pumped Conditions

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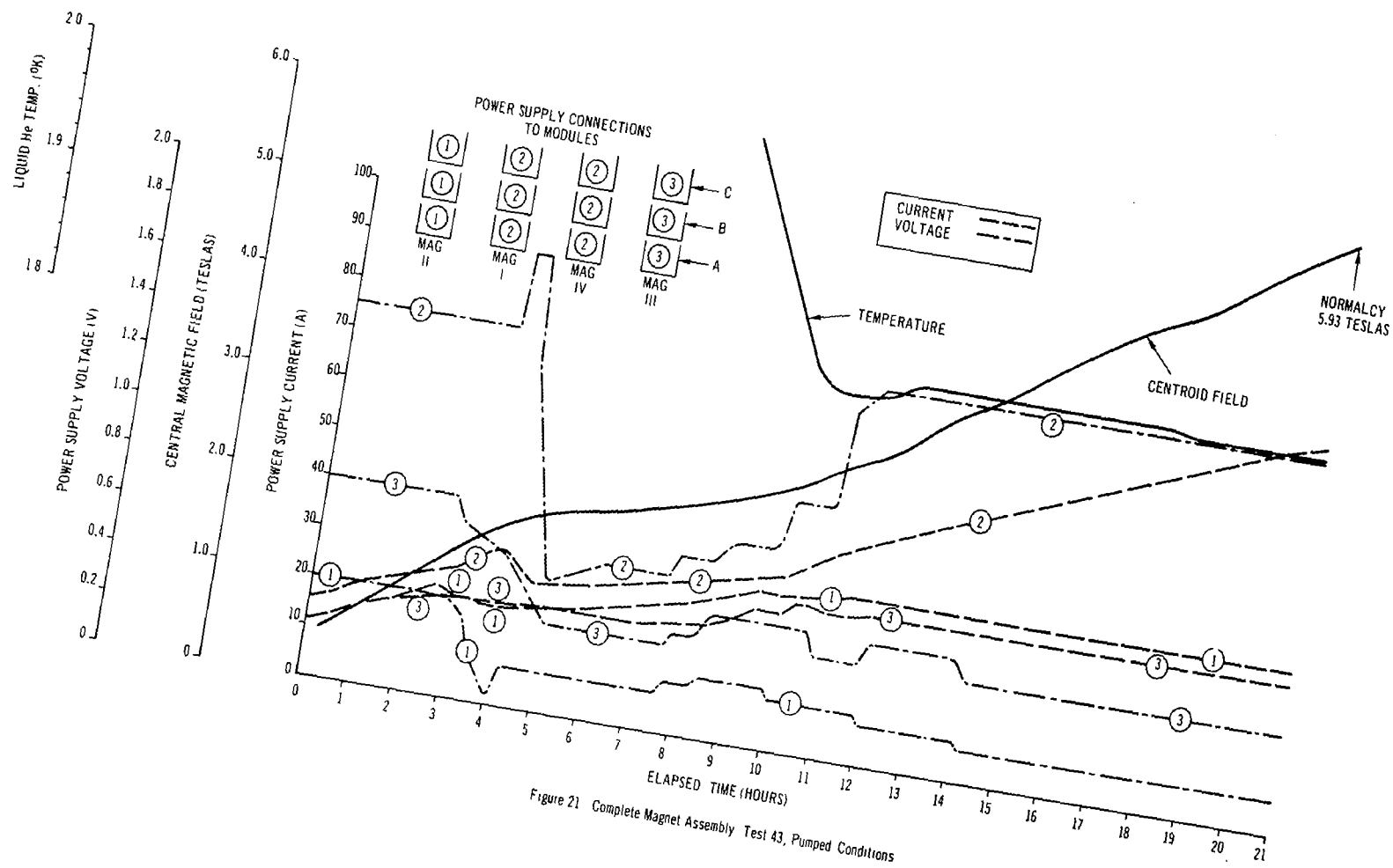
The two center magnets charged continuously until normalcy occurred at 5.93 Teslas. Subtracting a maximum contribution of 0.57 Tesla by the two end magnets, the two center magnets contributed approximately 5 Teslas, which is less than their contribution when the pair was tested alone. A review of detailed tracings from this test and subsequent tests of the four-magnet assembly did not result in isolation of a unique problem area to account for the reduced performance. It must be construed, therefore, that the often-noted increase in magnet current degradation with increase in magnet size is a contributing mechanism in this case. Although this effect has been attributed qualitatively to increased adverse energy inputs resulting from increase in inductive coupling, there is not yet a satisfactory quantitative explanation.

There is little doubt that other combinations of module and magnet charging currents might yield higher fields than the approximately 6 Teslas achieved in test 43. The effort necessary to attempt this increase, however, is outside the scope of the existing contract.

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

Although the specified 7.2-Tesla magnetic field was not attained, the work performed established a relatively clear set of criteria to guide future designs. There is no problem where the device for which a magnet system is being designed does not constrain severely the volume occupied by the windings, because fully stable operation at low current densities can be employed. Where consideration of higher current densities with some inherent instability is a necessary factor, experience with similar magnets must be available to permit reliable extrapolation to any given design. The expected current density, therefore, must be as much a part of the overall device design (i.e., a plasma system) as is any other constraint. For the project described in this report, the requirements of the remainder of the system were established initially, and the volume left for the windings was a result. Impressive successes on previous smaller superconductive magnets gave no obvious reason why the goal could not be attained.

Once within the confines of a given high current density for a design, there are several possible optimizing factors. The instabilities inherent in superconductive magnets are influenced adversely by very high inductances. Magnetoresistive probes, built into the windings of the modules tested for this contract, clearly showed oscillatory, fast-changing patterns of magnetic field, even though the centroid field showed a steady monotonic behavior. Rapid field changes were the result of applying different charging voltages to individual modules and consequent reactions due to the high mutual coupling and shorting within winding layers. Local regions of the windings, therefore, were subject to unpredictable field excursions, with all of the adverse possibilities of large dipole loops being set up in the ribbon. Substituting fewer high-current turns that are striated or stranded to reduce inductance and magnetization is clearly a requirement for magnets such as the magnet assembly described in this report.

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Because related practical matters (e.g., available conductor sizes and power supplies) might limit the extent to which inductance can be reduced, a second optimizing factor is the degree of stabilization that can be achieved by the normal metal coating on the ribbon. Silver plating 0.0254 mm thick per side on the 2.28-mm-wide ribbon (such as was wound into magnets I, III, and IV) was quite adequate for early small high-field magnets. This ribbon performed well, with some reservations due to excessive charging times, in the 15-cm-bore, 14-Tesla magnet made for NASA by RCA. This magnet contained over 90 kilometers of ribbon. It since has became obvious, however that the current density actually attained drops faster due to instabilities than due to dilution of the winding volume by adding normal metal as magnets get larger. Magnet II (copper-clad version) shows, therefore, that better results are achieved in this case by stabilizing to a point that might be wasteful for a smaller magnet.

Specifications for the magnet assembly probably would have been met under reduced-temperature conditions if all four magnets had been wound with copper-clad ribbon. With this ribbon paralleled to form high-current conductors (e.g., 1.77 cm wide), materially reducing the inductance, specifications probably could have been met at 4.2°K operation. Due to the lack of a quantitative model, however, which can reduce such designs to standard engineering practice, it remains necessary in all cases to have related experience with any one kind of fabrication before proceeding with a major effort.